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COMPUTER INVESTIGATION
OF A
DESTROYER STEAM GENERATOR

Leslie F. Creager
Joseph D. Fenick, Jr.
Gerald H. O'Brien

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Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
ELECTRICAL ENGINEERING

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ABSTRACT

The steam generator of a DLG-9 destroyer is investigated and simulated by means of a digital computer program which was developed for this thesis. The Bailey Meter Company combustion control system is analyzed by separate control loops. The entire steam generator and control systems are simulated and compared with data from the DLG-9 test boiler. An attempt to obtain transfer functions for the boiler dependent upon steam flow is made and the results are analyzed.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation for the encouragement and guidance given them by Professor Milton L. Wilcox and Doctor George J. Thaler of the U. S. Naval Postgraduate School in this investigation of a destroyer steam generator.

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1. Introduction

1.1 Discussion

The United States Navy has long been interested in the automation of the steam propulsion system of a surface combatant ship. This project as envisioned would be directed at the automation of the main propulsion plant to permit centrally controlled automatic operation from full power ahead to full power astern, and would extend to the supplementary operating procedures such as lighting off, warming up, transferring the electrical load, securing the plant and so on. The decision of such a control system must ensure that the system be simple and highly reliable, provide minimum response time in the plant to load demand changes, and provide efficient operation with a minimum of personnel to operate and maintain the plant.

The Navy would like to employ a computer control installation which would take over in a natural progression of functions from human operators. The plan would proceed from unattended operation of the propulsion plant over the complete range of ship's power through startup and shutdown into the supplementary operating procedures where the cost savings and increased effectiveness to be had by computer automation can be studied.

The advantage of such a computer control system would be fully realized on Destroyer Type ships whose operations may be divided into three situations:

First, the battle situation in which not only the highest possible performance of all a ship's system is required, but also the maximum ability to recover from any damage or derangement short of destruction of the ship. This, in the case of the Destroyer, includes anti-submarine warfare in which the ship may proceed at flank speed to the search point, then slow down

drastically while conducting the sonar search.

Second, the maneuvering, station-keeping and mooring situation in which step changes in demand, either up or down, and in rapid succession would be made on the propulsion plant. In this situation and in the one above, the fastest possible reaction time by the control system and the plant are desired short of dangerous overloads on any system components.

The third situation is that of steady steaming such as when the ship is transiting between port and training areas, or deploying. Normal in-port auxiliary steaming falls into this caetgory. Under these conditions optimum fuel economy is a paramount consideration, and efficiency of boiler operation is the controlling factor.

In addition to the automation of propulsion control, the control computer can be applied to the supplementary functions that were mentioned above such as lighting off and securing, which would include shifting between the in-port and underway steaming conditions, the transferring of machinery loads for purposes of equalizing operating hours or in response to a casualty, and the operation of the electric power generating system which is intimately related to the management of the propulsion plant. There are a number of peripheral functions which lend themselves to computer control such as, the operation and distribution of the fresh and feed water distilling plant, the transfer and distribution of fuel oil from storage to service tanks and to control list, trim, and stability, and to diagnose and correct engineering casualties. Damage control effectiveness could be improved by processing the information influx in the computer, which could supply solutions to the assessed damage such as the routing of casualty power, counter flooding, and stability analysis. Another function of the computer could be the routine maintenance programming through monitoring of

equipment hours and scheduling of maintenance to fit the ship's operating schedule and internal resources.

In the area of engineering casualty control the advantage of digital computer control can be demonstrated. It is conceivable that the job of automating the plant can be accomplished by simply mechanizing the obvious functions of a finite number of men by analog devices located at or near their watch stations. However, the not-obvious functions of these men are the difficult ones to replace. Each man monitors many plant variables, primarily temperatures, pressures, valve positions, and the on or off condition of the machinery units. Each man has stored information resulting from training and experience which he calls upon to make small adjustments to manipulate variables and to react correctly to excursions of important variables, which comprise actual or incipient engineering casualties. Now if the men themselves are to be on call, but not on station, the automatic control system must be able to scan all the plant variables which the men monitor. It must, furthermore, be programmed to initiate immediately casualty control measures adequate to protect the plant from damage and to give on-call personnel time to respond. These functions call for an information handling and selective response capability which no practical analog device could handle. This requirement on the control system stems from reliability problems of the machinery systems themselves and their susceptibility to derangement due to operational stresses or in battle. It is anticipated that the reliability of a digital computer control system can be made to far exceed anything which can be expected of the machinery itself.

In order to undertake this project careful analysis and a mathematical representation of the propulsion system and particularly of the boiler, with the subsequent simulation of the system on a computer is necessary.

It also would be desired to implement the automatic control system on a destroyer-type ship which has an existing automatic combustion control device. This pneumatic automatic combustion control device regulates fuel, air, and feed water to the boiler by monitoring outlet steam pressure and feedback readings of the three manipulative variables. A predetermined air-to-fuel ratio is set into the device and some allowance is made for the longer response time of the forced draft system to changes in steam demand than that of the fuel oil system. The control device is capable of safely controlling the boiler over the full range of steam demands, from stop to full power and back to stop.

The Naval Boiler and Turbine Laboratory has conducted extensive tests on a boiler from a DLG type ship, which has an automatic combustion control system as described above, and through a perturbation type analysis developed a system of transfer functions for the pneumatic control system and transfer functions for the boiler at two operating points [1] .

By employing these transfer functions, the boiler and its associated control systems can be simulated on a computer and further study as to the response of the boiler to different demands can be accomplished at a minimum of expense. In this thesis the air, fuel, and water systems will be analyzed separately and then combined with the known transfer functions of the boiler at the two operating conditions, namely that of cruising condition and 90 percent of full power and the plant will be run as a delta model. Next an attempt will be made to simulate the operation of the boiler and control systems between these two operating points so that an accurate mathematical model of the boiler and automatic combustion control system will be available for later implementation into the digital computer control scheme.

The simulation will be done on a digital computer by means of a program

which utilizes analog computer techniques on a digital computer. This program was developed by the authors for use on a Control Data Corporation 1604 Digital Computer and is an adaptation of Program JANIS [2]; it will be referred to as Program ANALOG in this thesis.

1.2 Results and Recommendations

The investigation of the various control loops of the Bailey Meter Company combustion control system showed that the fuel flow and air flow control systems were represented by a true mathematical model; however, the water flow system as represented by NBTL [1] was oscillatory and the authors feel that further study of this model of the DLG-9 boiler is necessary. The combustion air flow control system was successfully converted from a "delta system" at two operating points to a non linear system which was a good mathematical representation of the entire boiler for a full range of operation.

The entire steam generator plant with the combustion control system was simulated at the two operating points given by NBTL [1] , namely, at the cruising condition and at the 90 per cent full power condition. The plant was then perturbated with a five per cent ramp change in steam flow both in positive and negative directions and the results were analyzed and found to compare favorably with expected results with the exception of the oscillatory water flow system. The entire plant was also tested using the same boiler linear transfer functions at cruising and 90 per cent condition and the non linear air flow control loop. A ramp change in steam flow from ten to 90 per cent of full power in 23 seconds was introduced into the mathematical models and the results were compared with data received from NBTL [4] for a similiar test of the actual DLG-9 test boiler. The results obtained by using the 90 per cent transfer functions were found to agree more favorably with the test data than those results obtained by using the cruising conditions transfer functions. The boiler transfer functions were then made functions of steam flow using the cruising conditions transfer functions for values of steam flow below cruising conditions, and using a straight line

approximation between the cruising conditions and 90 per cent conditions transfer functions for steam flow in between those two operating points. The same ten to 90 per cent steam flow ramp was introduced into this simulation, but the results did not agree with the test data as well as using the 90 per cent transfer functions.

It is recommended that this work be continued and if possible there should be an attempt made to obtain transfer functions for an operating point of the DLG-9 boiler at or about ten per cent of full power and at another operating point between cruising and 90 per cent full power. With this information a better representation of the boiler may be possible since the authors believe that the values of the boiler transfer functions are some function of steam flow and a more complete mathematical description of the boiler would be available with the addition of these two operating points. If the above recommendation cannot be accomplished, then, by the results of this thesis, using the 90 per cent transfer functions will result in a good approximation of the boiler response.

Using these ideas, a new non-interacting type of controller can be designed which employs a digital control computer which will give better responses in steam pressure and drum water level to rapid changes in steam flow, than is now possible with the existing Bailey Meter Company combustion control system.

2. Program Analog

2.1 Discussion

Program Analog is a digital computer program which allows problems to be described in an analog computer type language. Such a language, which is in the form of Laplace Transforms, is convenient for simulations made by scientists and engineers. The program actually builds up an interconnection of the simulated analog computer blocks (integrators, summers, multipliers, etc.) from a set of subroutines corresponding to each of the blocks. In setting up a simulation the programmer defines the interconnection structure between the blocks in a separate subroutine, sets the gain and parameter adjustments for each block, and sets the initial conditions for the variables.

A flow chart of the program is shown in figure 2-1. There are about twenty different kinds of operational blocks. They all use subscripted quantities for all block parameters and variables. In this way each subroutine may be used as many times as desired. The only constraint is that the total number of blocks may not exceed 98. Similar to the analog computer, special purpose blocks can be constructed in the same format as the others standard subroutines.

The individual performing a simulation writes subroutine DIAGRAM which is merely a sequence of Fortran CALL statements which specify the interconnection of the blocks. Each block used in the simulation is given a number. This number is used in specifying parameters for that block. Similarly each variable output is numbered. This number is independent of the block number, but for simplicity the same number is usually chosen for each. Two blocks are connected together by giving the same variable number to the output of one block and the input of the other.

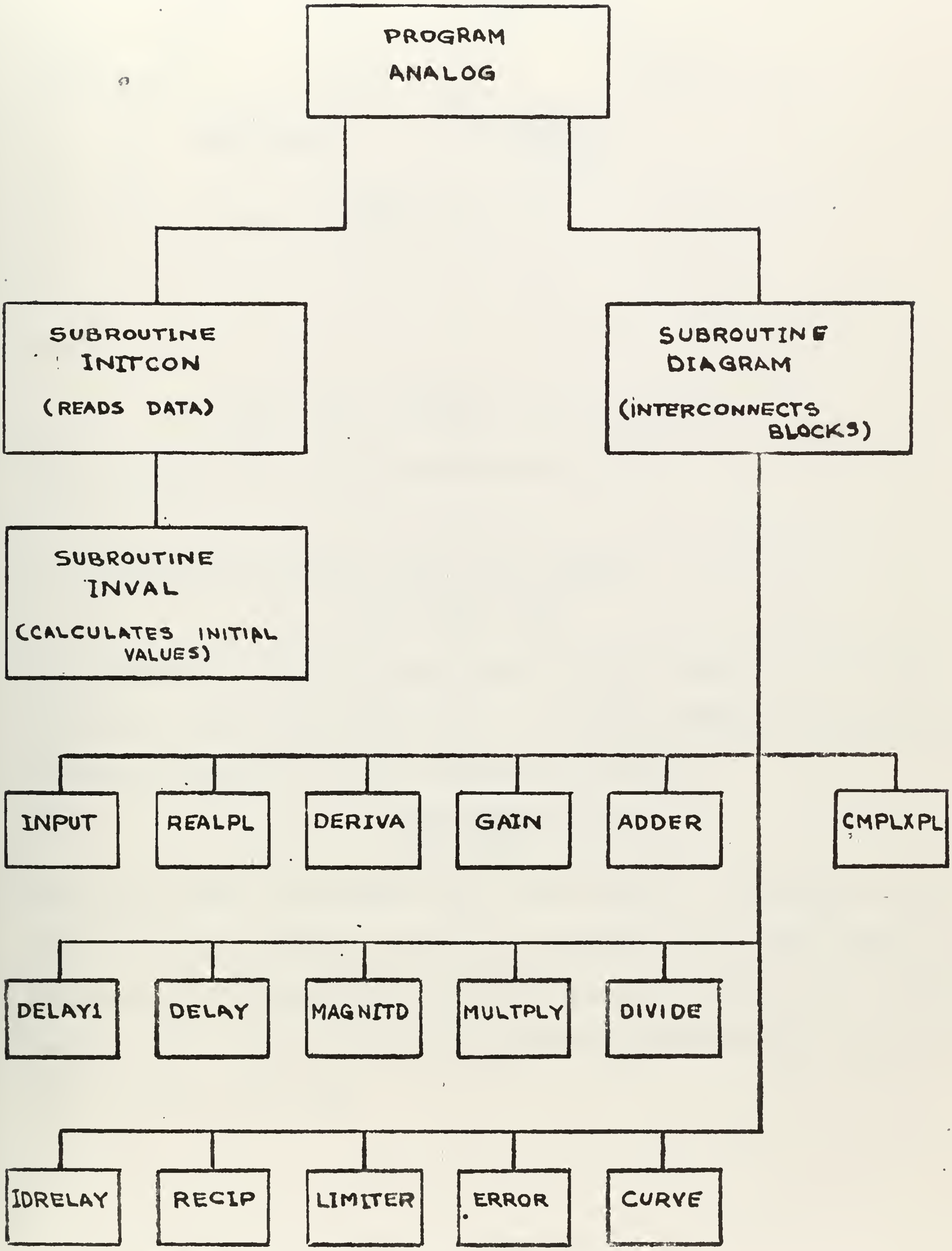


Figure 2-1 Program Analog Block Diagram

As an example:

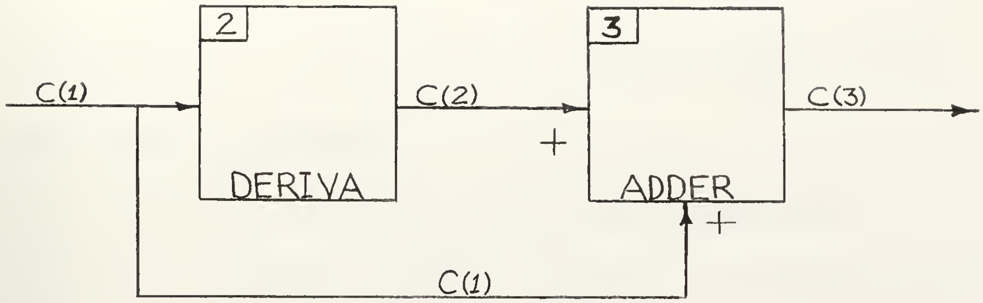


Figure 2-2(a) Example of a block sequence

In this sequence one would be generating the formula

$$y = x + \dot{x}$$

or in terms of the variables used in the program

$$C(3) = C(1) + C(2)$$

All subroutines are called in the form (N, I, J,..) where N is the block number, I is the output number, and J,.. the input number(s). The calling sequence which would be in this subroutine DIAGRAM is:

```
CALL DERIVA (2,2,1)
CALL ADDER (3,3,1,2,0)
```

C(1) is the input to the DERIVA block, block number 2. The output is C(2) which is now the derivative of C(1). In the ADDER block, block number 3, the inputs are C(1) and C(2). These two variables are added, thus producing variable C(3). The zero in the calling sequence indicates that there is no third variable to be added.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

2.2 Digital and Analog Comparison

Some differences exist between this method of simulation and a true analog computer. Listed below are some advantages of each.

2.21 Digital Advantages

1. No voltage or time scaling is required.
2. Greater precision is possible, and there is no noise.
3. Nonlinearities can quite easily be simulated.
4. There is practically no limit to problem size.
5. Delay, multiplication, limiting, etc. can be simulated exactly.

2.22 Analog Advantages

1. Actual equipment can be connected in the simulation.
2. For simple problems a simple computer only is needed.
3. Simulation is continuous without the need for sampling; thus there is no sampling error involved.
4. Continuous functions, such as integration, can be simulated exactly.
5. The entire simulation proceeds simultaneously with no closed loop delay.
6. It is possible to watch the program run and make on the spot adjustments in gains, initial conditions, etc.
7. Problem run time is independent of problem size.

2.3 Analog Subroutines

There are sixteen types of simulations available for the programmer's use, which are stored in the basic program as subroutines and are called for and interconnected in subroutine DIAGRAM. The following is a list of the available subroutines, their usage, the equivalent equation, and the data required:

<u>INPUT</u>

Usage: CALL INPUT (N, I, J)

Equivalent Equations: $C(I) = G(N) + H(N)(t) + P(N) \sin Q(N)t$

Data input required: G(N), H(N), P(N), Q(N)

<u>REALPL</u>

Usage: CALL REALPL (N,I,J)

Equivalent Laplace equation: $C(I) = \dfrac{C(J) * G(N)}{s + H(N)}$

Date input required: G(N), H(N) Note that H(N) is set equal to zero for straight integration.

<u>DERIVA</u>

Usage: CALL DERIVA (N,I,J)

Equivalent Laplace equation: $C(I) = sG(N)\ C(J)$

Data input required: G(N)

<u>GAIN</u>

Usage: CALL GAIN (N,I,J)

Equivalent equation: $C(I) = G(N)\ C(J)$

Data input required: G(N)

<u>ADDER</u>

Usage: CALL ADDER (N, I, ± J, ± K, ± L)

Equivalent equation: $C(I) = \pm C(J) \pm C(K) \pm C(L)$

Data input required: None. For adding only two variables, L must be zero.

CMPLXPL

Usage: CALL CMPLXPL (N,I,J)

Equivalent Laplace equation: $C(I) = \dfrac{G(N)\ C(J)}{s^2 + H(N)\ s + P(N)}$

Data input required: G(N), H(N), P(N)

DELAY1

Usage: CALL DELAY1 (N,I,J) N = 1,2,3

Equivalent Laplace equation: $C(I) = C(J)\ e^{-G(N)s}$

Data input required: G(N). A variable may be delayed for a maximum of 1000 time increments. Only three Delay 1 blocks are available.

DELAY

Usage: CALL DELAY (N,I,J)

Equivalent equation: $C(I) = 0 \quad t < G(N) \quad C(I) = C(J) \quad t \geq G(N)$

Data input required: G(N)

LIMITER

Usage: CALL LIMITER (N,I,J)

Equivalent equations:

$C(I) = G(N) * C(J); \quad P(N) < G(N)C(J) < H(N)$

$C(I) = H(N) \qquad G(N)\ C(J) \geq H(N)$

$C(I) = P(N) \qquad G(N)C(J) \leq P(N)$

Data input required: G(N), H(N), P(N)

IDRELAY

Usage: CALL IDRELAY (N,I,J)

Equivalent equations:

$C(I) = G(N) \qquad C(J) \geq 0.$

$C(I) = H(N) \qquad C(J) < 0.$

Data input required: G(N), H(N)

MULTPLY

Usage: CALL MULTPLY (N,I,J,K)

Equivalent equation: $C(I) = C(J) * C(K)$

Data input required: None.

MAGNITD

Usage: CALL MAGNITD (N, I, J)

Equivalent equation: $C(I) = |C(J)|$

Data input required: None.

DIVIDE

Usage: CALL DIVIDE (N, I, J, K)

Equivalent equation: $C(J) = \frac{C(J)}{C(K)}$

Data input required: None.

RECIP

Usage CALL RECIP (N, I, J)

Equivalent equation: $C(I) = \frac{G(N)}{C(J)}$

Data input required: G(N)

ERROR

Usage: CALL ERROR (N,I,J,K)

Equivalent equation: $C(I) = \frac{1}{T}\int_{0}^{T} (C(J) - C(K))^2 \, dt$

Data input required: None

INVAL

This is a dummy subroutine in the main deck which is called by putting a minus sign in column 1 of data card 3. (See Data Preparation) It is written by the programmer in order to let the computer calculate the initial conditions of the variables.

As an example:

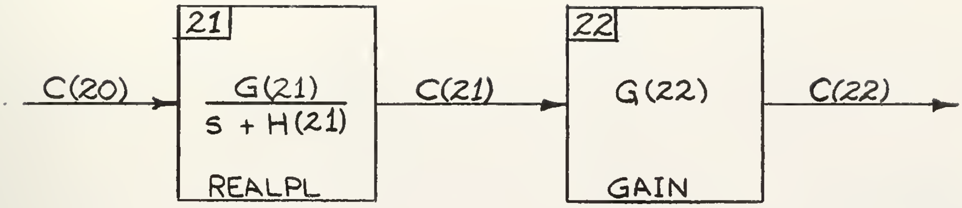


Figure 2-2(b) Example for INVAL

The initial value of C(22) has been read in. The sequence for the initial conditions to be set on variables C(21) and C(20) is:

```
C(21) = C(22)/G(22)
C(20) = C(21)*H(21)/G(21)
```

These two cards are inserted in the INVAL subroutine immediately after the COMMON cards.

CURVE

Usage: CALL CURVE (NO,I,J)   NO = 1,2,..,9

This subroutine allows up to 9 curves, each curve having up to 50 breakpoints. Unlike other subroutines, the first argument, NO, refers to the number of the curve vice the box number. For example;

CALL CURVE (2,7,22)

generates a value for C(7) as a function of variable C(22) according to curve 2. The set of breakpoints, x_1, y_1, x_2, y_2, ...x_k, y_k are entered as data (See data preparation) and a continuous curve is generatedby a series of straight line segments.

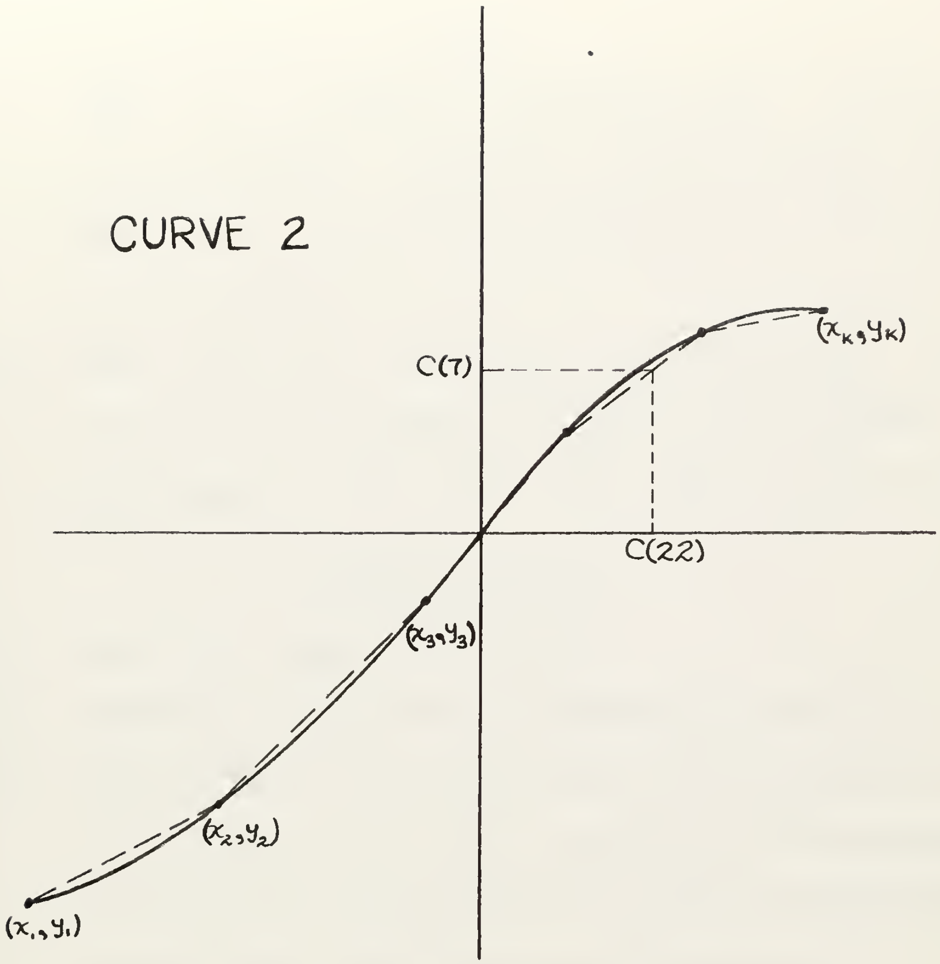


Figure 2-3   Example for Subroutine CURVE

2.4 Data Preparation

The input data required is as follows:

1. FORMAT (I3) The number of block data cards. One card with a 0 or - in colum 1 followed by a two digit number in columns 2 and 3. The minus sign indicates that there is curve data to be read in.

2. FORMAT (I2, 5E10.4) Block data cards in any order. Each card contains the block number in columns 1 and 2 followed by the input data, G(N), H(N), P(N), Q(N), R(N), for that block.

- - - - - - - - - - - - - - - - -
omit if no curves

2a. FORMAT (I1) The number of curves.

2b. FORMAT (I2) The number of breakpoints for Curve 1.

2c. FORMAT (2E20.5) The coordinates of the breakpoints for curve 1 (x_1, y_1, y_2,...,x_k, y_k). One card for each coordinate. The number of cards must equal the number of breakpoints. Continue data cards 2b and 2c for each curve.

- - - - - - - - - - - - - - - - -

3. FORMAT (I3) Number of initial condition cards. One card with a 0 or a - in column 1 followed by a two digit number in columns 2 and 3. The minus sign will call INVAL, a subroutine written by the programmer which automatically sets the initial conditions of the variables. The use of INVAL is optional.

3a. FORMAT (I2,E20.6) Initial condition cards in any order. Each card contains the variable number in columns 1 and 2 followed by the initial condition for that variable.

4. FORMAT (F10.5) Time increment for computation.

5. FORMAT (F10.5) Total time of run.

6. FORMAT (F10.5) Time interval between periodic print outs.

7. FORMAT (F10.5) Time interval between periodic graph points. A maximum of 900 graph points will be plotted.

8. FORMAT (2I2) Variables to be printed. First variable number to be printed in columns 1 and 2. Last variable to be printed in columns 3 and 4. The first, last, and all inclusive variables will be printed according to the time interval between periodic printouts.

9. FORMAT (I2, 6A8) Number of graphs desired in column 2 (5 maximum). Name, etc. in the next 48 columns. This information will appear on every graph.

10. FORMAT (2I2,6A8) One data card for each graph desired. A two digit number in columns 1 and 2 for the variable which is to appear as the X coordinated, and a two digit number in columns 3 and 4 for the variable which is to appear as the Y coordinate. If time is desired as a coordinate 99 is to be used as the variable number. Graph title, etc., in the next 48 columns. This information appears only on the graph indicated on that data card.

2.5 Example

In order to show the validity of such a digital computer program a third order system with two nonlinearities was chosen and set up on the analog computer [5] and on the digital computer using program Analog. The system chosen was critical in that the response was unstable for a voltage input of 10.2 volts. The amplifiers in the acceleration and tachometer feedback channels were set to saturate at three volts. The three volts on the digital was an exact quantity, whereas the three volts on the analog was nominal as one would expect using diodes. The Analog digital program block diagram is shown in figure 2-4 and the analog computer cirucit diagram is shown in figure 2-5. Subroutine Diagram and the data for program Analog is shown in figure 2-6. The comments in figure 2-6 explain the meanings of the data cards and are not part of the data. Figures 2-7 and 2-8 are the time responses of the Analog program and the analog computer respectively. The two traces are almost identical with the exception of the output of the saturated amplifiers, and the reason for that is explained above.

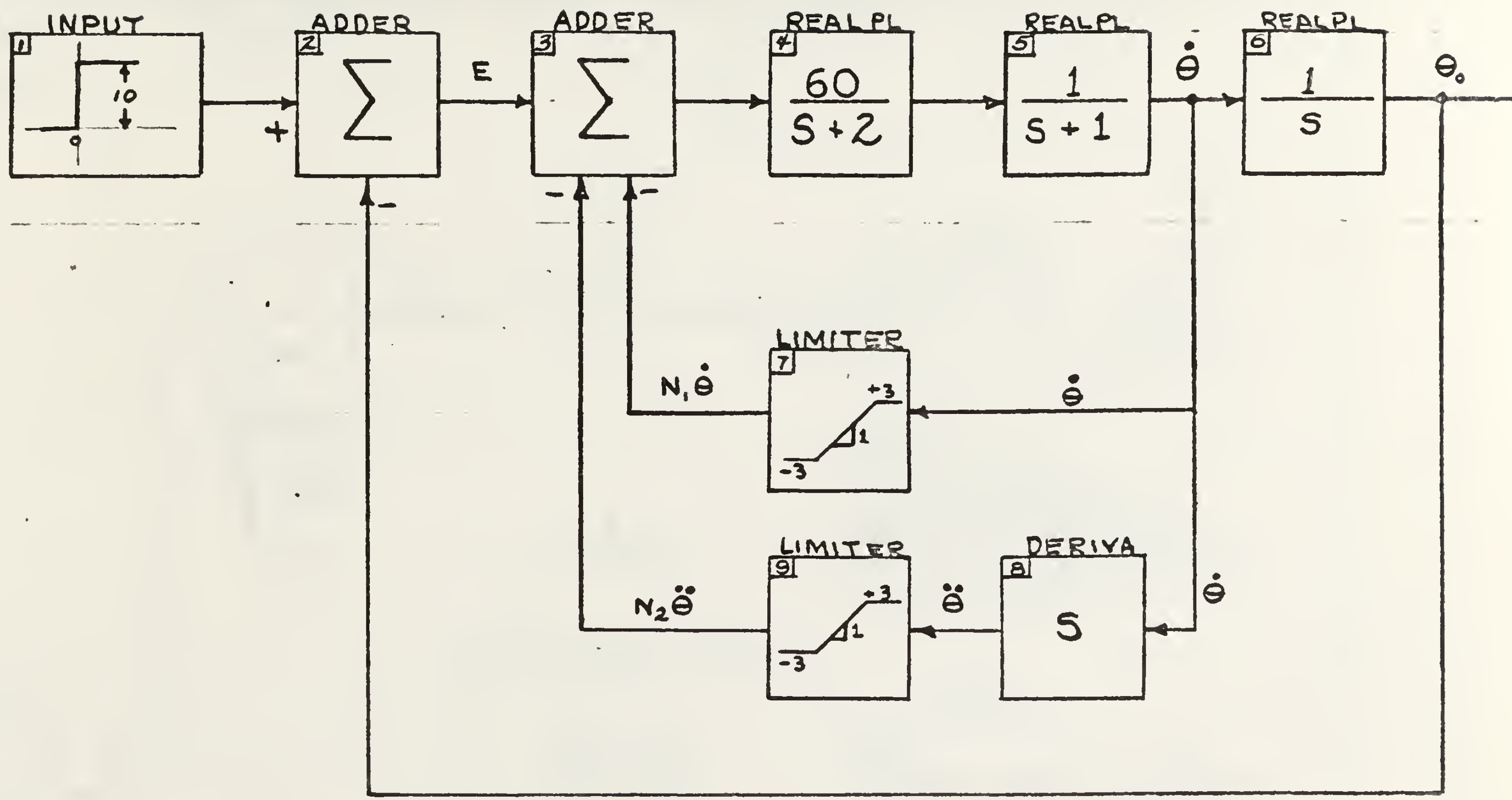


Figure 2-4 Example third order system

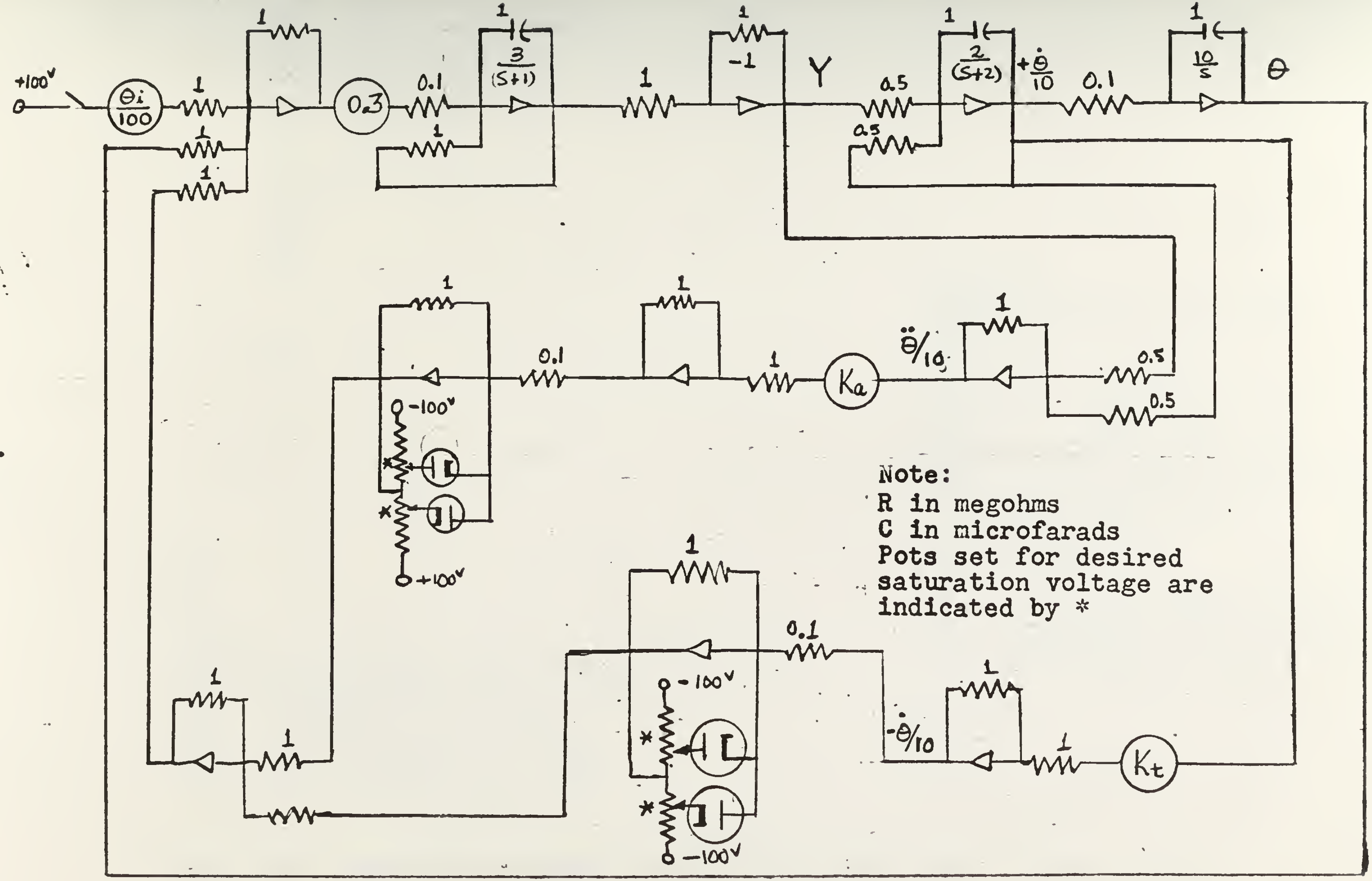


Figure 2-5 Analog Computer simulation for example third order system

```
      SUBROUTINE DIAGRAM
      CALL INPUT(1,1)
      CALL ADDER(2,2,-6,1,0)
      CALL ADDER(3,3,2,-7,-9)
      CALL REALPL(4,4,3)
      CALL REALPL(5,5,4)
      CALL LIMITER(7,7,5)
      CALL DERIVA(8,8,5)
      CALL LIMITER(9,9,8)
      CALL REALPL(6,6,5)
      RETURN
      END
      END
                                                  COMMENTS
   7                                             NUMBER OF BLOCKS WITH DATA
  1   10.                                        STEP OF 10
  4   60.      2.                                G(04)=60.  H(04)=2.
  5   1.       1.                                G(05)=1.   H(05)=1.
  6   1.                                         G(06)=1.  SINCE H=0 REG INTEG
  7   +1.      +3.        -3.                    GAIN=1.0  UPPER LIMIT  3
  9  1.0       +3.       -3.                     LOWER LIMIT -3 BLOCKS 7 AND 9
  8  1.0                                         GAIN OF DERIVATIVE IS 1.0
                                                 NO INITIAL CONDITIONS
.002                                             TIME INCREMENT
12.                                              LENGTH OF RUN
.1                                               PRINT THE VARIABLES EVERY .1SEC
.02                                              PLOT VARIABLES EVERY .02 SEC
 208                                             PRINT VARIABLES 2 TO 8 (.1SEC)
 5 FENICK  PROGRAM TEST THIRD ORDER SYSTEM       FIVE GRAPHS CALLED FOR
9909  N2 THETA DOT DOT VS TIME
9905   THETA DOT  VS TIME                        TITLES
9908   THETA DOT DOT VS TIME                     OF
9906  THETA (OUTPUT) VS TIME                     GRAPHS
9907   N1 THETA DOT VS TIME
```

Figure 2-6 Subroutine DIAGRAM and data for third order system example

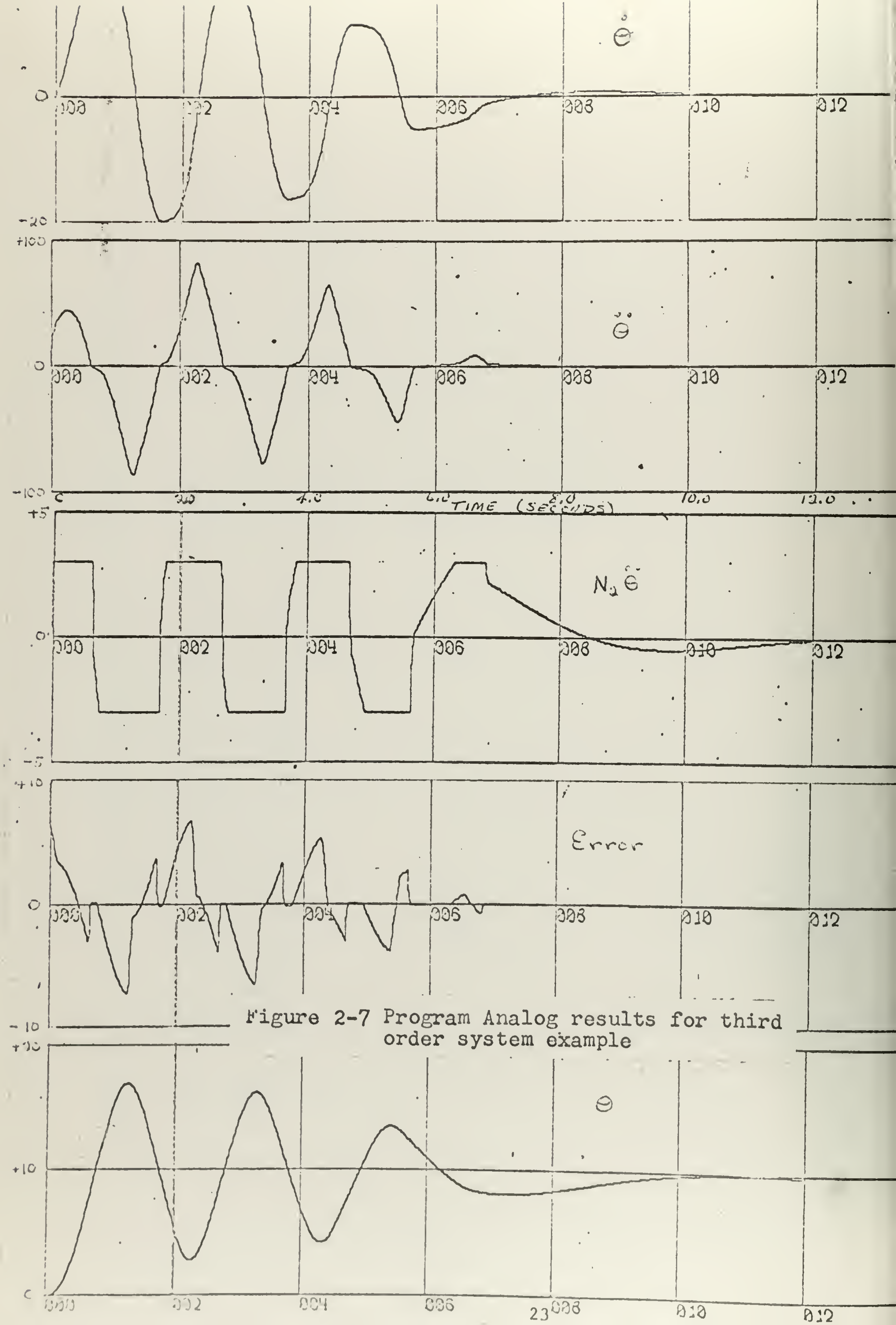


Figure 2-7 Program Analog results for third order system example

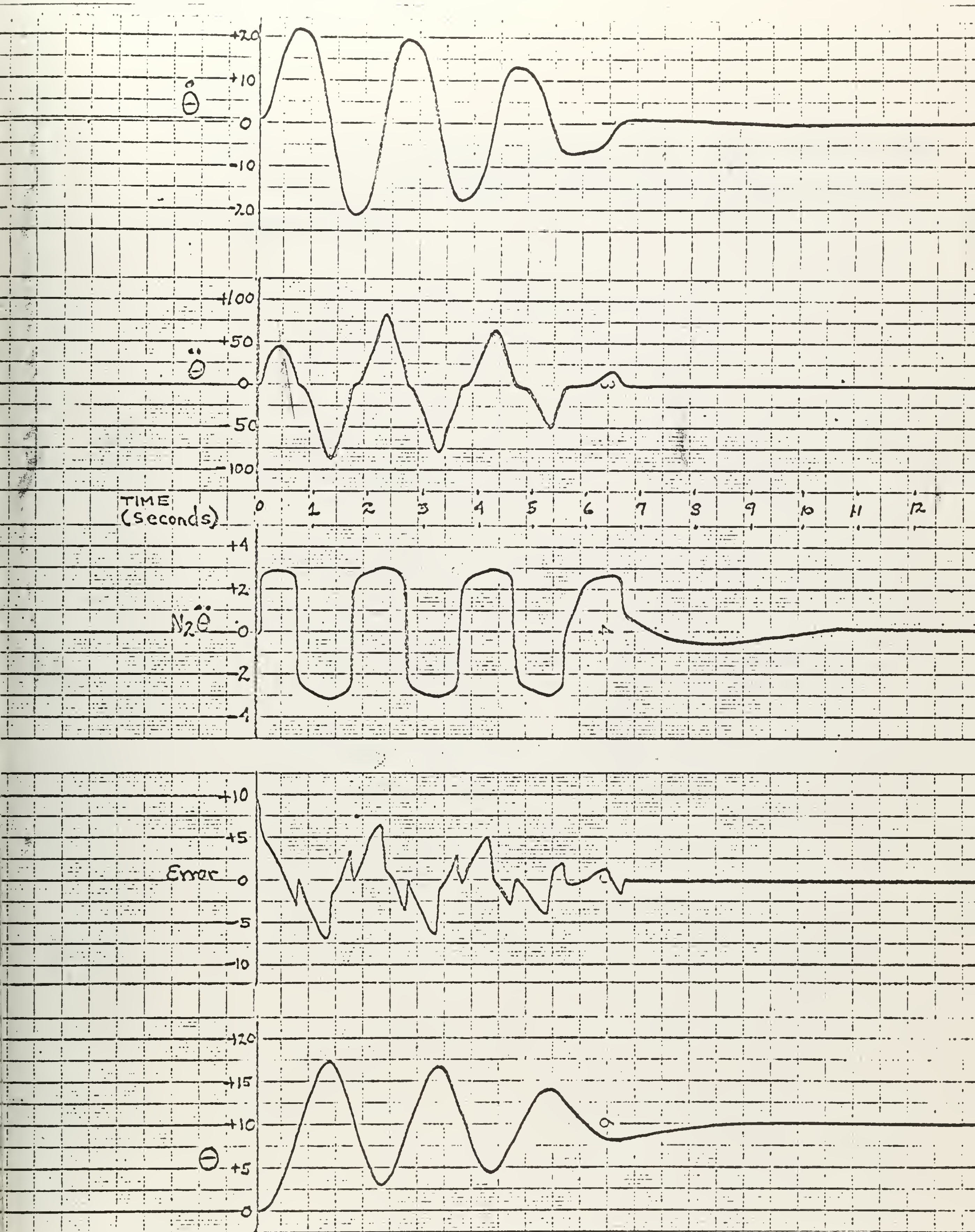


Figure 2-8 Analog Computer results for third order system example

2.6 Conclusion

Examination of the response curves of program Analog indicates that the digital computer program accurately simulates an analog representation of a control system.

3. The Bailey Combustion Control System.

3.1 Discussion

The Bailey Combustion Control System is utilized on the DLG-9 boiler which this thesis investigates and analyzes. This section describes how the combustion control system operates, and gives general descriptions of various components of the system, which will be further amplified in greater detail in later sections.

The boiler steam drum pressure is measured in the steam pressure transmitter that develops an air loading pressure proportional to steam pressure. Since the pressure transmitter is measuring steam pressure over a range from 900 psig to 1500 psig, it will produce an air loading pressure over a range of three to 27 psig in direct proportion. Since loading pressure is proportional to steam drum pressure it can be substituted for steam pressure, and become the steam drum pressure measurement in the control system.

The steam flow is measured by a flow transmitter which develops an air loading pressure that is directly proportional to steam flow. Since the DLG-9 boiler has a full power generating capacity of 166,000 pounds of steam per hour, the flow transmitter will vary its output loading pressure from three to 27 psig as the steam flow is changed from zero to 166,000 lbs/hr. If the boiler is generating 50 percent of full power (83,000 lbs/hr), the transmitter will send an air loading pressure of 15 psig (50 percent scale).

The amounts of fuel, air, and feedwater required depend upon two facts: (1) the amount of steam being used and (2) the desired pressure to be maintained. This designates steam flow as our index to changes in boiler load, and steam pressure as the correction factor to set the desired standard.

The steam flow signal is transmitted to a master relay where the steam flow measurement is exactly reproduced. The steam pressure is transmitted to the same relay where it is balanced against a reference force that represents the desired steam pressure. Any difference between the actual steam pressure and the reference set point will have an inverse effect on the output of the relay. The output signal from the master relay becomes the boiler load demand signal calling for a corresponding firing rate.

To illustrate more clearly, suppose the boiler is generating steam at 25 percent of its rated capacity, and steam pressure is being maintained at 1200 psig. The steam flow meter is sending nine psig to the master relay, which in turn develops the same pressure. Since the steam pressure is equal to the desired value, there is no difference, and has no effect on the demand signal. The firing rate of the boiler is equal to 25 percent called for by the master relay. Now the engine throttles are opened, increasing the steam flow from 25 to 50 percent of boiler full power. The increased steam flow results in an increase in boiler demand signal, this is almost instantaneous, however, due to the lag in the response of pumps, blowers, and heat transfer the boiler does not immediately increase its generating rate. This results in a decrease in steam pressure. The difference in actual pressure versus desired reference causes the master relay to increase its output a proportional amount which calls for a firing rate in excess of the rate called for by steam flow. This is called overfiring, and is necessary to overcome the various time delays encountered in the control and plant systems. With the firing rate now greater than steam flow, steam pressure is more quickly restored to the desired value.

On a decrease in steam demand, the firing rate is decreased simultaneously with steam flow but the residual heat in the boiler tends to increase

the steam pressure slightly. This then calls for firing at rates less than steam flow or underfiring.

It becomes readily apparent here, that deviations in steam pressure, during changes in load is nothing more than a function of the characteristics of the boiler and its auxiliary machinery.

The master demand signal is transmitted to an air flow demand Standatrol, and through a limiting relay, to an oil flow Standatrol. A Standatrol is Bailey Company's trade name for their standard proportional plus reset controller. In the air flow Standatrol the master demand signal is balanced against the air flow measurement and the output pressure from the Standatrol serves to position the forced draft blower throttles and air flow control dampers. The Standatrol is calibrated to maintain a constant output pressure as long as the air flow measurement is equal to the demand signal. When the demand signal increases calling for more air flow, the Standatrol will commence increasing, at a rate depending upon the relay's proportional band and reset settings, until the air flow again balances the master demand. The air flow is measured by a transmitter taking the drop of flue gases across a section of the economizer and extracting the square root. This air flow transmitter signal goes to a calibrating relay, referred to as the excess air relay, which has remote bias and proportional band adjustments. These adjustments permit the operator to regulate the amount of excess air for economy haze, smokeless operation, or to blow tubes. The output of the excess air relay is transmitted to the air flow Standatrol. With this arrangement any master demand value will result in the forced draft blowers running at a speed that will provide a corresponding air flow regardless of the characteristics of the blower throttles or the number of blowers in use.

The control of the oil flow is similar to the Air Flow Control System except for the inclusion of the fuel limiting relay. Since the slow inertia of the blowers causes air flow to lag behind the steam flow on an increase in load, it would be possible to admit oil to the boiler before there is sufficient air to burn it. For this reason the master demand signal is piped to the fuel limiting relay along with the air flow measurement from the excess air relay. The fuel limiting relay is calibrated so that its output pressure can never be greater than the air flow measurement, but on a sudden decrease in load, the output can decrease at the same rate as the master demand regardless of how long it takes the blowers to slow down and decrease the air flow. The output from the fuel limiting relay is transmitted to the oil flow Standatrol whose principle of operation is identical to that of the air flow Standatrol.

On the DLG-9 boiler the fuel flow metering system is of the return flow burner type of fuel oil system. In this system, oil is pumped to the burners at a constant pressure of 1000 psi and at a relatively constant rate per burner. The design of the burner is such, that if permitted, the fuel can flow by the atomizer through the return line to the pump. The fuel that is not returned is sprayed into the fire box and burned. A control valve is installed in the return oil line and by closing or opening the valve, the amount of fuel sprayed into the fire box will be increased or decreased. The output from the oil flow Standatrol positions the oil flow control valve.

An areameter transmitter is installed in both the supply and return fuel lines and each develops an air loading pressure proportional to their respective oil flows. These supply and return flow signals are transmitted to a totalizing relay where an output pressure is developed that is proportional to the flow of fuel into the boiler by subtracting the oil returned

signal from the oil supplied signal. This fuel burned measurement is transmitted to the oil flow Standatrol and balanced against the oil demand signal from the fuel limiting relay.

As in the air flow control, a linear relationship between the master demand signal and oil flow is maintained regardless of the flow characteristics of the burners or the number of burners in use.

The DLG-9 boiler employs the three-element feedwater control system which is the standard metered system that is widely used in the Navy. The basic control elements consist of steam flow as the demand index, water flow as the response impulse, and boiler drum level as the supervisory impulse. The steam flow and water flow transmitters sense the differentials created by flow nozzles in the steam header and the feedwater header and send out corresponding air pressures. These signals are applied to a ratio relay which develops a set point signal representative of normal steam drum level when the steam flow and water flow are equal. Any unbalance between steam flow and water flow will shift the set point for water up or down depending on the direction of unbalance. This signal is applied to the feedwater standardizing relay where it is compared to the actual steam drum level signal. The steam drum level is measured by a bellows type force balance differential transmitter. The transmitter measures level by comparing the actual drum level against a reference head, and the measurement is indicated by a pointer directly powered by the bellows mechanism. The transmitter also develops an air loading signal that is directly proportional to the steam drum level in inches.

Any error between the measured drum level and the set point is recognized in the feedwater standardizing relay which sends a signal corresponding to this difference to the proportional plus reset feedwater controller. The signal from the feedwater controller positions the feedwater

control valve which admits more or less feedwater to the boiler depending on the signal.

The Bailey Combustion Control System as described in this section is in use in the Navy on destroyers and, with some modifications, on some aircraft carriers. As was pointed out in the thesis introduction there remains much to be done to improve the response of the boiler to sudden changes in load especially in the destroyer type ships; this is intimately related to the type of combustion control system which controls the boiler. Thus by analyzing and investigating the Bailey Combustion Control System and the boiler on DLG-9, the authors feel that through this work adaptive type control improvements may be forthcoming, and it is a necessary step towards the design of a digital computer control system.

4. Combustion Air Flow Control System

4.1 Discussion

The air flow control system is comprised of a typical feedback system including two principal nonlinearities, the steam control valves, and the forced draft blowers themselves. The system is composed of:

a. Proportional Plus Reset Air Flow Controller (Bailey Meter Company "Mini - Line" Standatrol)

b. Proportional Plus Rate Action Controller (Bailey Meter Company Rate Booster Relay)

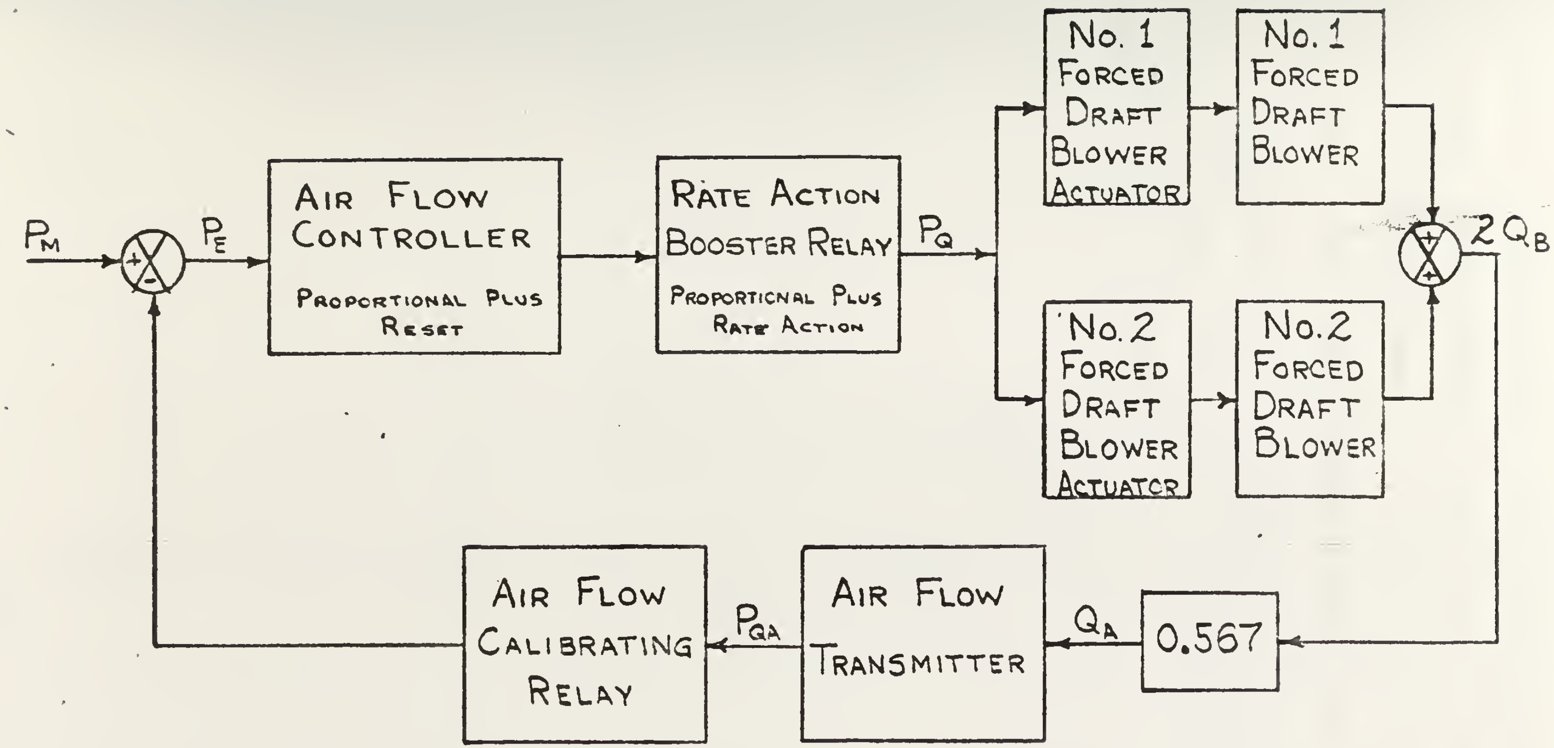
c. Forced Draft Blower Actuator, Linkage, and Throttle Valve (Bailey Meter Company Model AC-44 Control Drive with Mason-Neilan Control Valve)

d. Carrier Corporation Main Forced Draft Blowers

e. Total Air Flow Transmitter (Bailey Meter Company Type CJ-20 Differential Transmitter with Type KC-16 Square Root Converter - Transmitter)

f. Air Flow Calibrating Relay (Bailey Meter Company Model AR-40 "Mini - Line" Relay).

The system is set up as in figure 4-1 with pneumatic signal Pm as the incoming signal, and the quality of air Qa as the output. The quality of air is defined as the amount of air flow in cubic feet per minute divided by the rated blower capacity (37,800 cubic feet per minute).



COMBUSTION AIR FLOW CONTROL SYSTEM

Figure 4-1

4.2 Proportional Plus Reset Air Flow Controller

This Standatrol is a pneumatic relay designed and calibrated to receive a loading pressure, Pe, representing the difference between the master demand signal from the steam pressure controller and the signal from the air flow measurement. The output of the Standatrol serves to position the forced draft blower throttles and the air flow control dampers.

The proportional plus integral controller is linear and has constants which are shown in figure 4-3. Its minimum output is zero psig and its maximum output is 30 psig.

N Blower Speed (RPM)	T Torque (lb-ft)	G Steam Flow (lb/hr)	T_A Driving Torque (lb-ft)	T_R Retarding Torque (lb-ft)	Blower Transfer Function $\left(\frac{\%\ \text{Blower Capacity}}{\text{lb/hr}}\right)$
1000	17	800	$0.0214G_B$	$0.0207N$	$K_{BLOWER}\left(\frac{1}{1+26S}\right)$
2000	42	1600	$0.0290G_B$	$0.0303N$	$K_{BLOWER}\left(\frac{1}{1+17.1S}\right)$
3000	79	2800	$0.0409G_B$	$0.0467N$	$K_{BLOWER}\left(\frac{1}{1+11.1S}\right)$
4000	138	4300	$0.0412G_B$	$0.0667N$	$K_{BLOWER}\left(\frac{1}{1+7.77S}\right)$
5000	220	6400	$0.0388G_B$	$0.0944N$	$K_{BLOWER}\left(\frac{1}{1+5.5S}\right)$
6000	326	9200	$0.036G_B$	$0.112N$	$K_{BLOWER}\left(\frac{1}{1+4.68S}\right)$
7000	449	12800	$0.032G_B$	$0.141N$	$K_{BLOWER}\left(\frac{1}{1+3.67S}\right)$
8000	596	18000	$0.0236G_B$	$0.156N$	$K_{BLOWER}\left(\frac{1}{1+3.32S}\right)$

Figure 4-2 Forced draft blower data

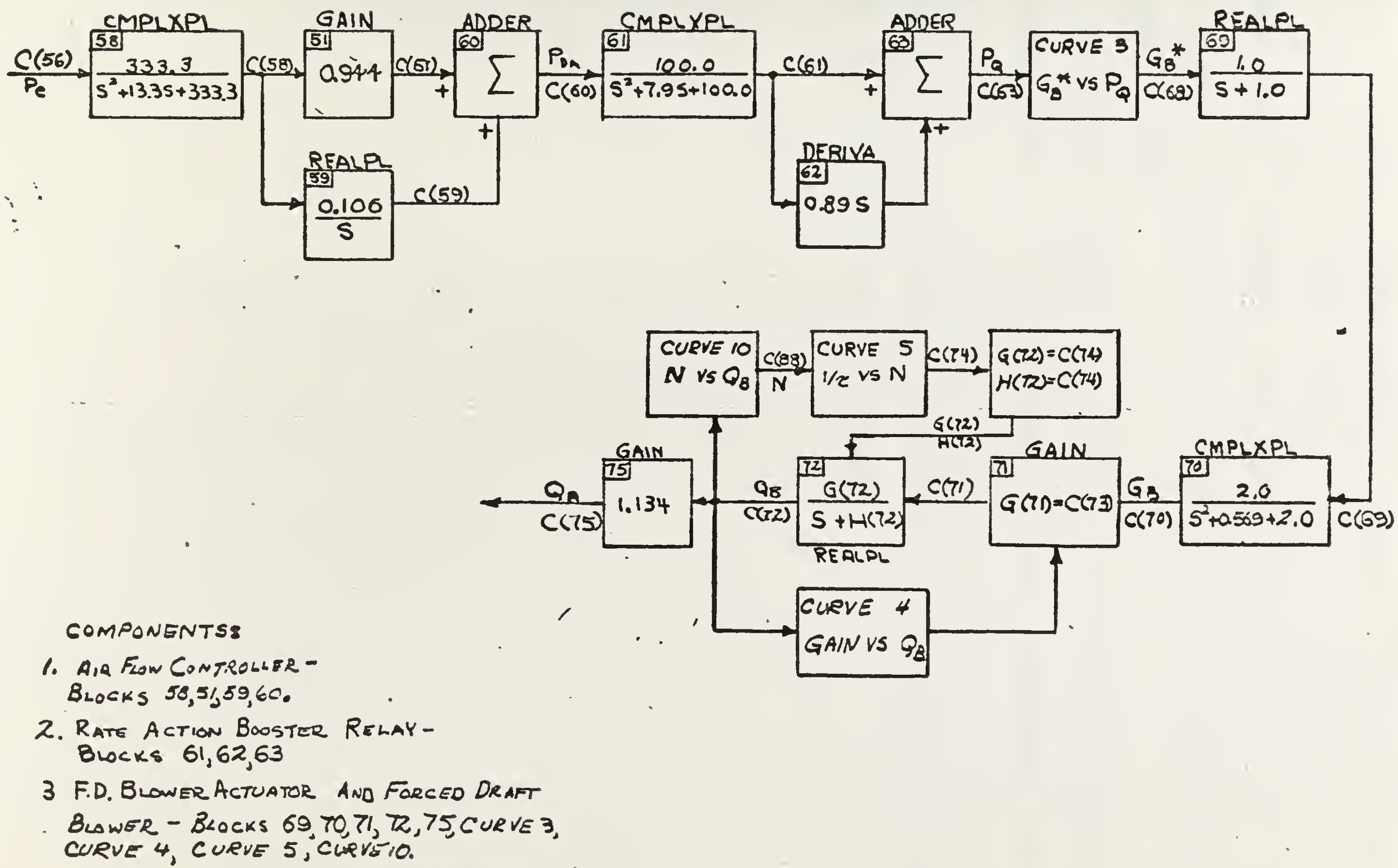


Figure 4-3 Program Analog simulation for combustion air system

4.3 Proportional Plus Rate Action Controller

This device is intended to provide increased phase margin in the blower control loop thus allowing maximum loop gain. The proportional plus integral Standatrol is calibrated to maintain a constant output pressure as long as the air flow measurement is equal to the demand signal. Should the demand signal increase, calling for more air flow, the rate action booster relay will commence increasing its output, Pq, at the rate set by the proportional band and reset settings until the air flow again balances the demand signal.

Proportional plus rate action devices unfortunately tend to act as noise amplifiers, and thus limiting action was encountered in the simulation; however, by proper choice of the time increment for the digital simulation the "noise effects" of the rate action booster relay can be diminished, and favorable results obtained.

[illegible]

[illegible]

[illegible]

4.4 Forced Draft Blower Actuator, Linkage and Throttle Valve

The pneumatic signal, Pq, from the rate action booster relay flows into the forced draft blower actuator positioning the throttle valve which admits the steam, Gb, to the forced draft blower turbine.

The blower speed versus loading pressure Pq, curve, figure 4-4, was obtained experimentally at NBTL [3] and since the limits of the pneumatic devices are between three and 27 psig, there are built in limits on the blower actuator, resulting in blower speeds not lower than 1800 RPM, nor higher than 7000 RPM.

The actuator dynamics are presumed to be linear for all blower speeds but the gain varies as the blower speed, figure 4-2. This non-linearity is due to the characteristics of the V - ported blower steam control valve.

The non-linear curve of blower steam flow, Gb, versus blower speed, N, figure 4-5, was obtained from the experimental data of figure 4-2, and since blower speed, N, versus loading pressure, Pq, figure 4-4, is available, a function generator (curve three of figure 4-3) can be obtained that relates blower steam flow, Gb, as a function of loading pressure, Pq, figure 4-6. Using this non-linear function generator, the blower steam flow feeds through the dynamics of the actuator into the forced draft blower.

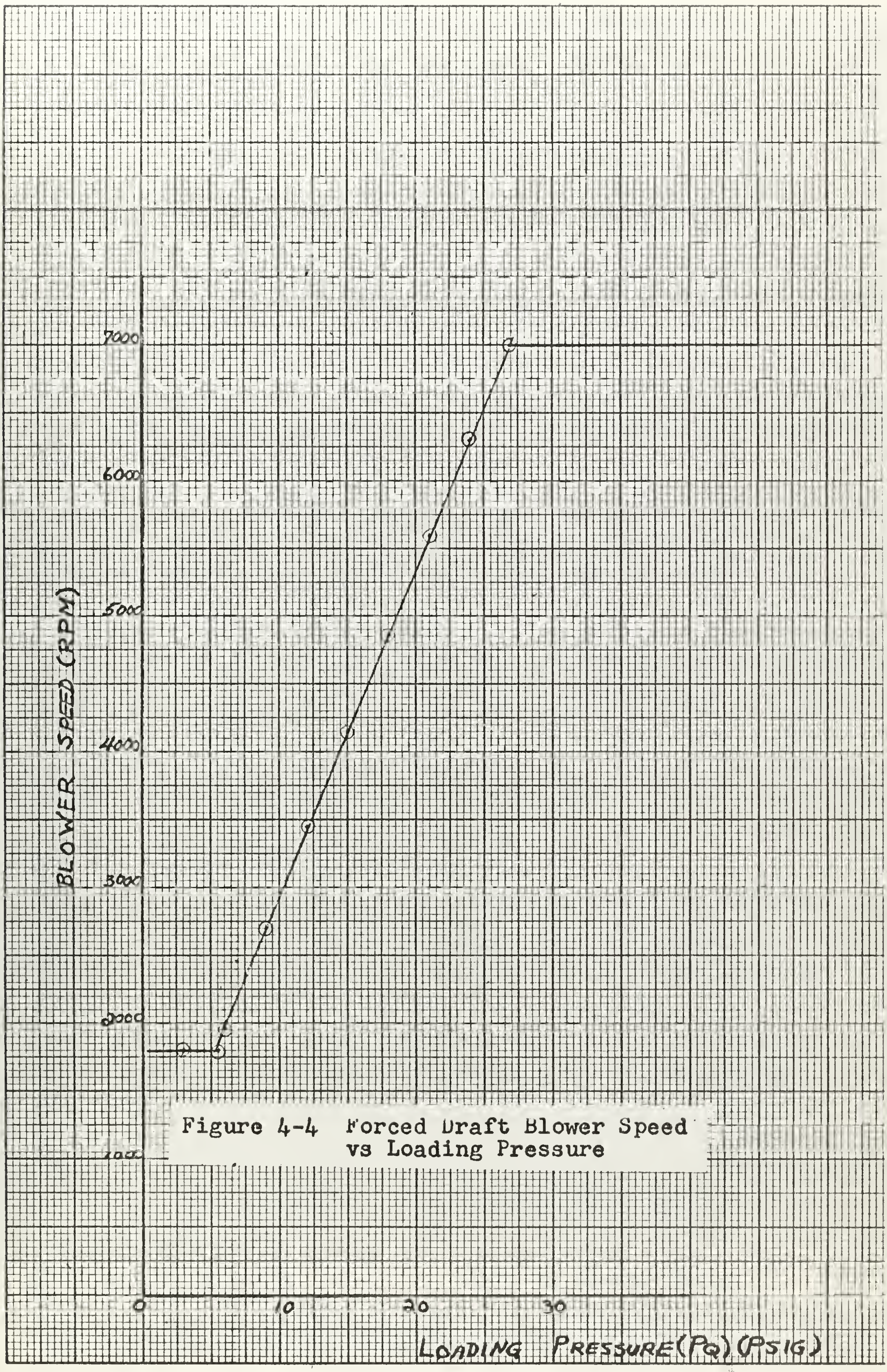


Figure 4-4 Forced Draft Blower Speed vs Loading Pressure

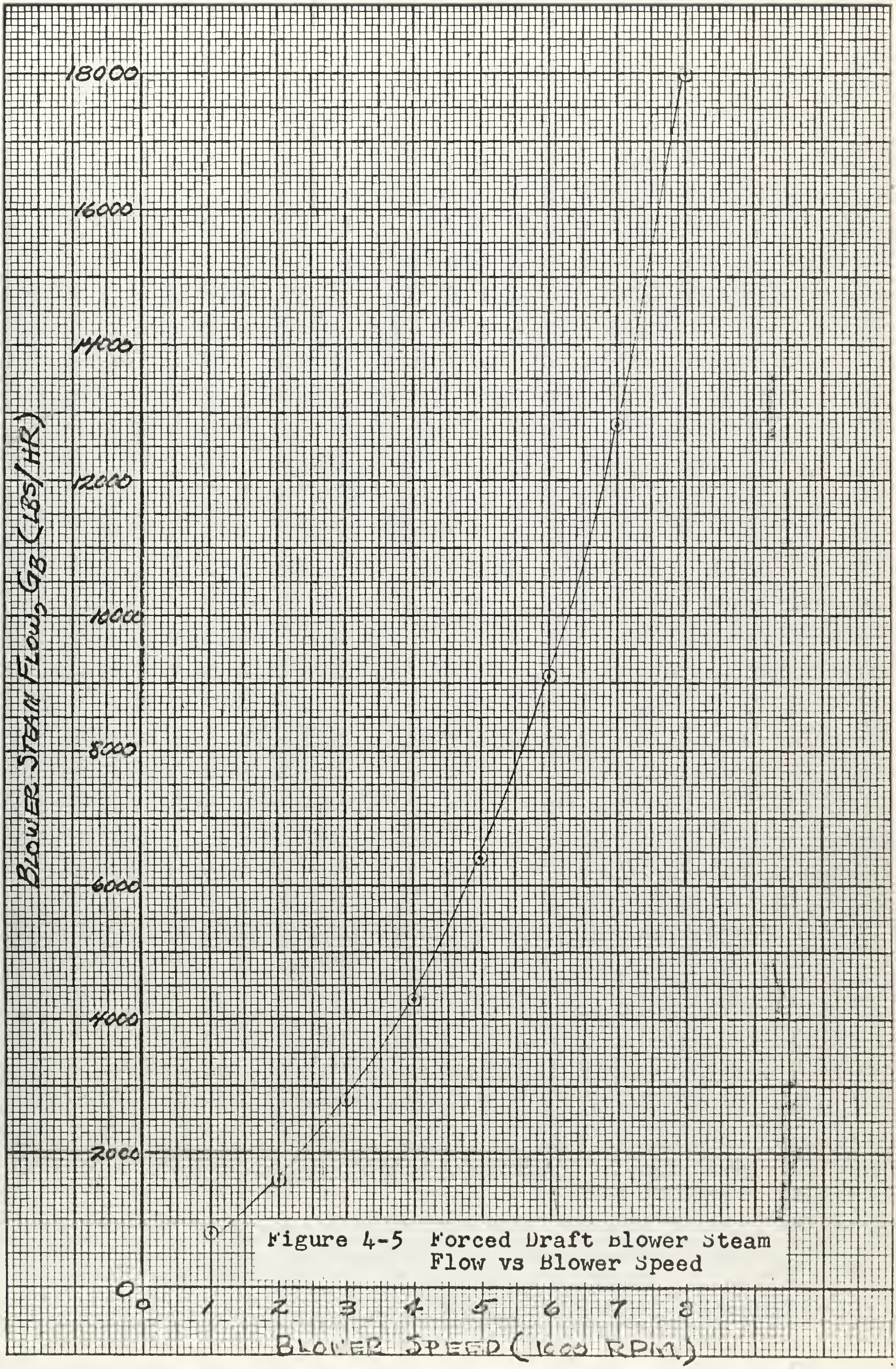


Figure 4-5 Forced Draft Blower Steam Flow vs Blower Speed

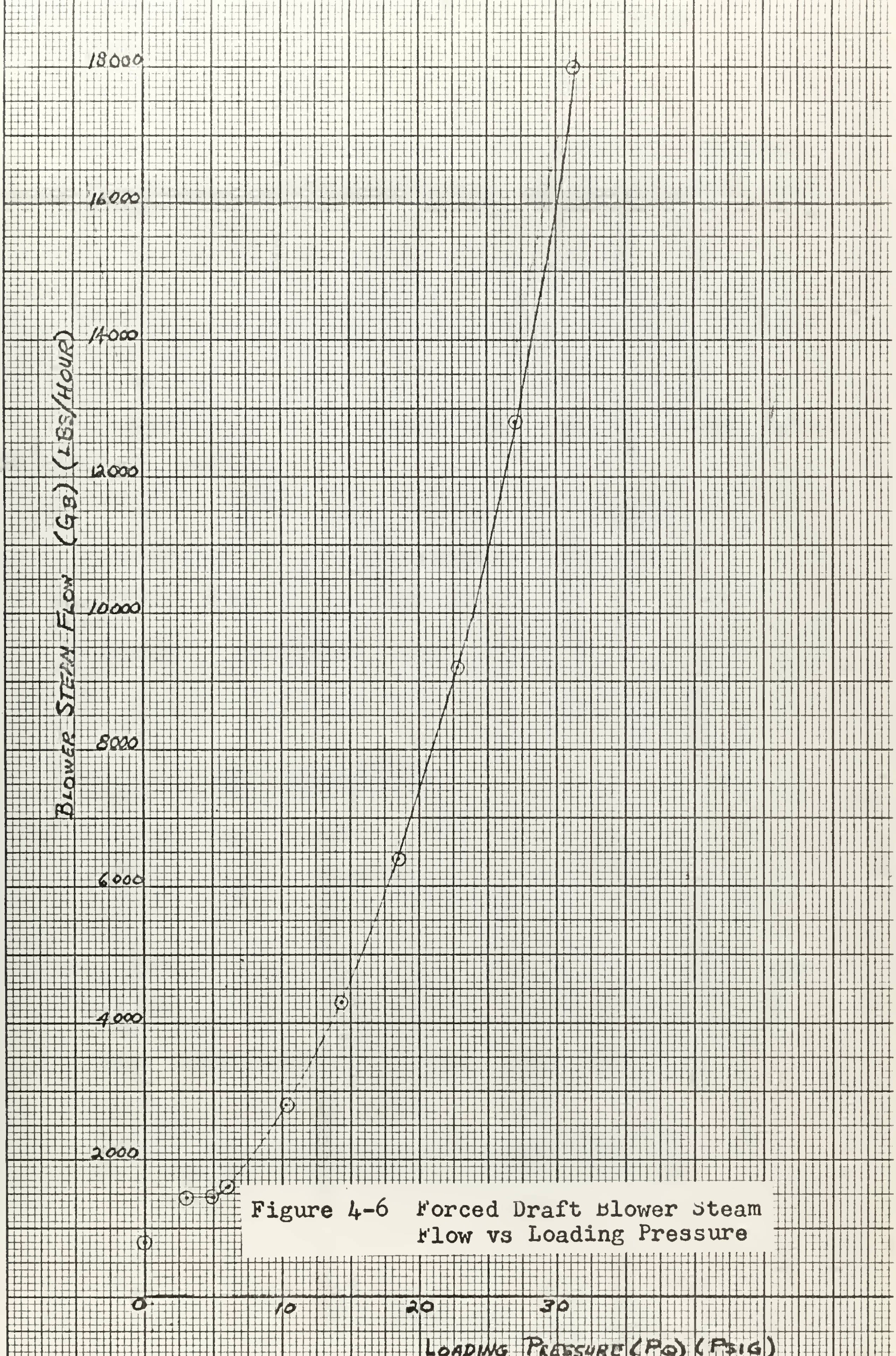


Figure 4-6 Forced Draft Blower Steam Flow vs Loading Pressure

4.5 Main Forced Draft Blower

The forced draft blowers are non-linear devices due to the driving torque and retarding torque being non-linear functions of turbine steam flow and blower speed.

The blower speed, N, versus air flow, Qb, is a non-linear function which was obtained from an experimental run on the DLG-9 test boiler at NBTL [3] some of the results of that run are tabulated in figure 4-7.

The sample calculation below illustrates how the blower speed N is related to the air flow Qb.

At 75 per cent of the boiler full power run (run number 421):

Blower output (air flow of two blowers) - 36,000 CFM

Boiler steam flow (Gs) - 130,930 lb/hr

Blower turbine steam flow (2 Gb) - 13,400 lb/hr

4.51 Determination of Qb by the Definition of the Quality of Air

$$Q_B = \frac{36{,}000 \text{ CFM/2 Blowers}}{(2 \text{ Blowers})(37{,}800 \text{ CFM})} = 47.7\% \qquad 4.1$$

4.52 Determination of Qb by Boiler Steam Flow

Following the flow of steam through the plant as shown in figures 4-8 and 4-3:

Pgs = (Steam flow Gs)(Steam flow transmitter gain) plus three psi offset.

$$Pgs = (130{,}930 \text{ lb/hr})(1.14 \times 10^{-4} \text{ psi/lb/hr}) + 3.0 \text{ psi} = 17.9 \text{ psi} \qquad 4.2$$

At the steady state value of 75% full power, from figure 4-8:

Pep = 0 and Pbq = Pm = Pgs = 17.9 psi

$$\text{thus } Qa = \frac{(\text{Pbq - three psi offset in calibrating relay})}{(\text{Calibrating relay gain})(\text{Air flow transmitter gain})}$$

RUN NUMBER	STEAM FLOW G_s (lb/hr)	PERCENT BOILER FULL POWER	BLOWER OUTPUT (CFM)	BLOWER TURBINE STEAM FLOW $2G_B$ (lb/hr)
418	55366	cruising	16290	5460
420	91590	55.2%	27820	9190
421	130930	75%	36000	13400
444	167710	101%	46820	23500
419	198930	120%	57130	30600

Figure 4-7 Experimental data from test run on DLG-9 Boiler

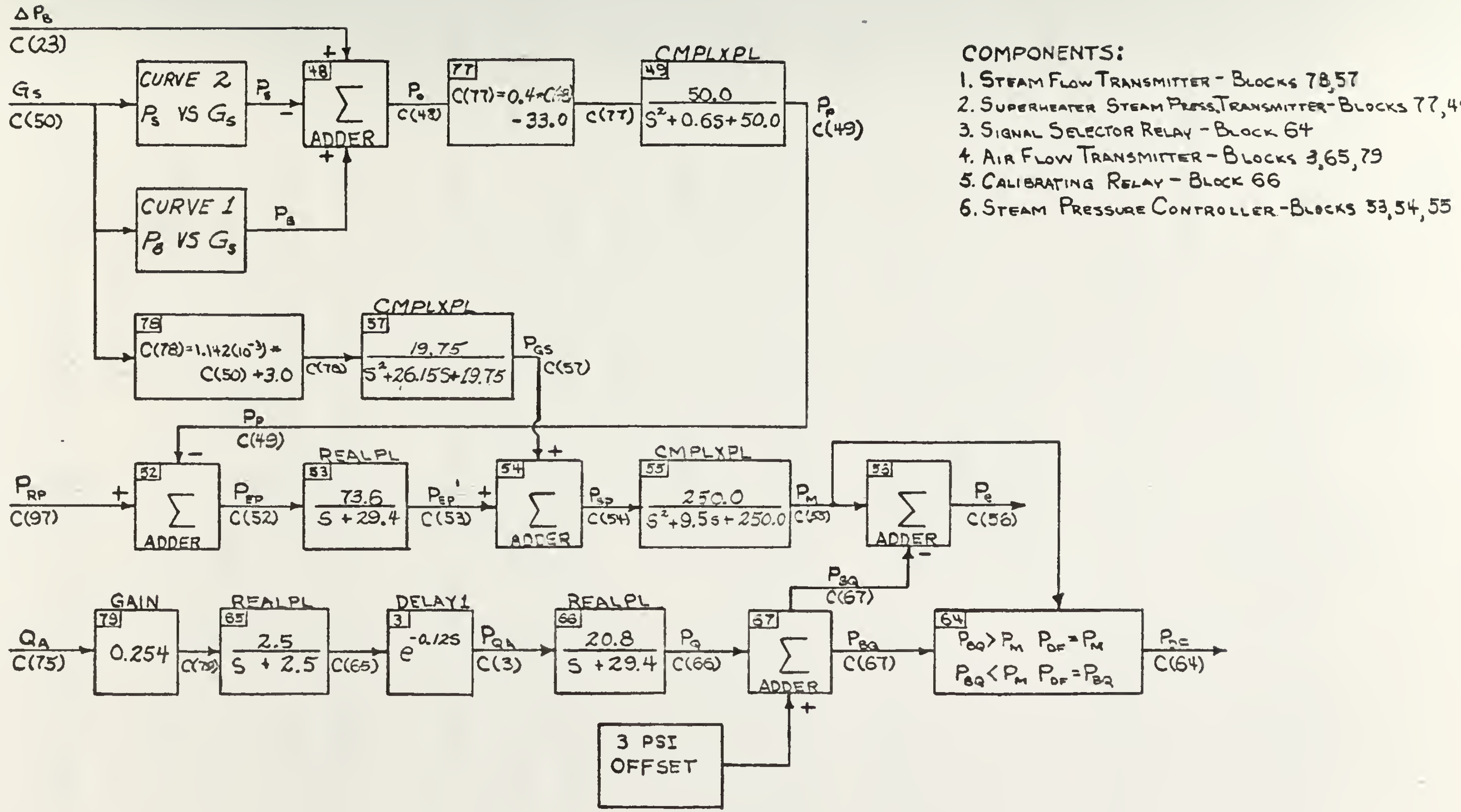


Figure 4-8 Program Analog simulation for steam pressure controller and associated equipment

$$Q_A = \frac{17.0\ \text{psi} - 3.0\ \text{psi}}{(1.05)(0.254\ \text{psi}/\%)} = 55.8\% \qquad 4.3$$

And from figure 4-3:

$$Q_B = \frac{Q'_A}{(2)(.567)} = 49.0\% \qquad 4.4$$

The two values of Qb are in close agreement, the latter value of 49.0% was used since the air flow measurement was not as accurate as the steam flow measurement.

4.53 Determination of Blower Speed as a Function of Blower Turbine Steam Flow

2 Gb = 13,400 lb/hr

Gb = 6,700 lb/hr

Entering figure 4-5 with 6700 lb/hr the corresponding blower speed is 5100 RPM.

Using the value of Qb of 49% and the corresponding speed of 5100 RPM, function generator (curve ten, figure 4-3) of blower speed N versus air flow Qb, figure 4-9, was obtained.

4.54 Forced Draft Blower Gain

The transfer function for the forced draft blower as noted in figures 4-2 and 4-7 are non-linear with the gain and the dynamics being functions of blower speed, N, or air flow, Qb, since by figure 4-9 these two parameters are related.

The gain function generator (curve four of figure 4-3) is a function of Qb and was determined from the data given in figure 4-7, as follows:

Using the data from run number 421:

Qb = 49.0%

Gb = 6700 lb/hr

thus blower gain is defined as Qb/Gb, and for this speed

Figure 4-9 Forced Draft Blower Speed vs Air Quality

$$\text{Blower Gain} = \frac{49.0\%}{6700 \text{ lb/hr}} = 0.00735 \qquad 4.5$$

At the low speeds, since the lowest value of loading pressure, Pq, is three psi, the corresponding blower speed is 1800 RPM, which gives a corresponding blower turbine steam flow, Gb, of 1440 lb/hr from figure 4-2. From experimental test run on the DLG-9 test boiler at NBTL [3] the corresponding air flow Qb is 6.35%. Thus the function generator relating blower gain to air flow, figure 4-10, was obtained.

4.55 Blower Time Constant

The time constant function generator (curve five of figure 4-3) is a function of blower speed and was determined directly from the data given in figure 4-2 in which the time constant τ is given as a function of speed, thus figure 4-11, $1/\tau$ as a function of blower speed, N.

By means of these various function generators the action of the main forced draft blowers can be simulated from ten percent to 120 percent of boiler full power.

4.6 Total Air Flow Transmitter

This instrument is designed to measure the pressure differential of the air flow across an orifice or restriction, extracts the square root of the differential pressure, and develops a pneumatic loading pressure that is proportional to the flow of the air. The air flow transmitter is simulated as shown in figure 4-8.

4.7 Air Flow Calibrating Relay

This relay, operating on the air flow transmitter output signal, Pqa, in the feedback circuit of the air flow control loop, is provided to permit scaling of the air flow open-loop gain in order to obtain optimum air to fuel ratio. The gain and bias are both remotely adjustable from the engine room control console, with the gain having a range from .5 to 20 and the

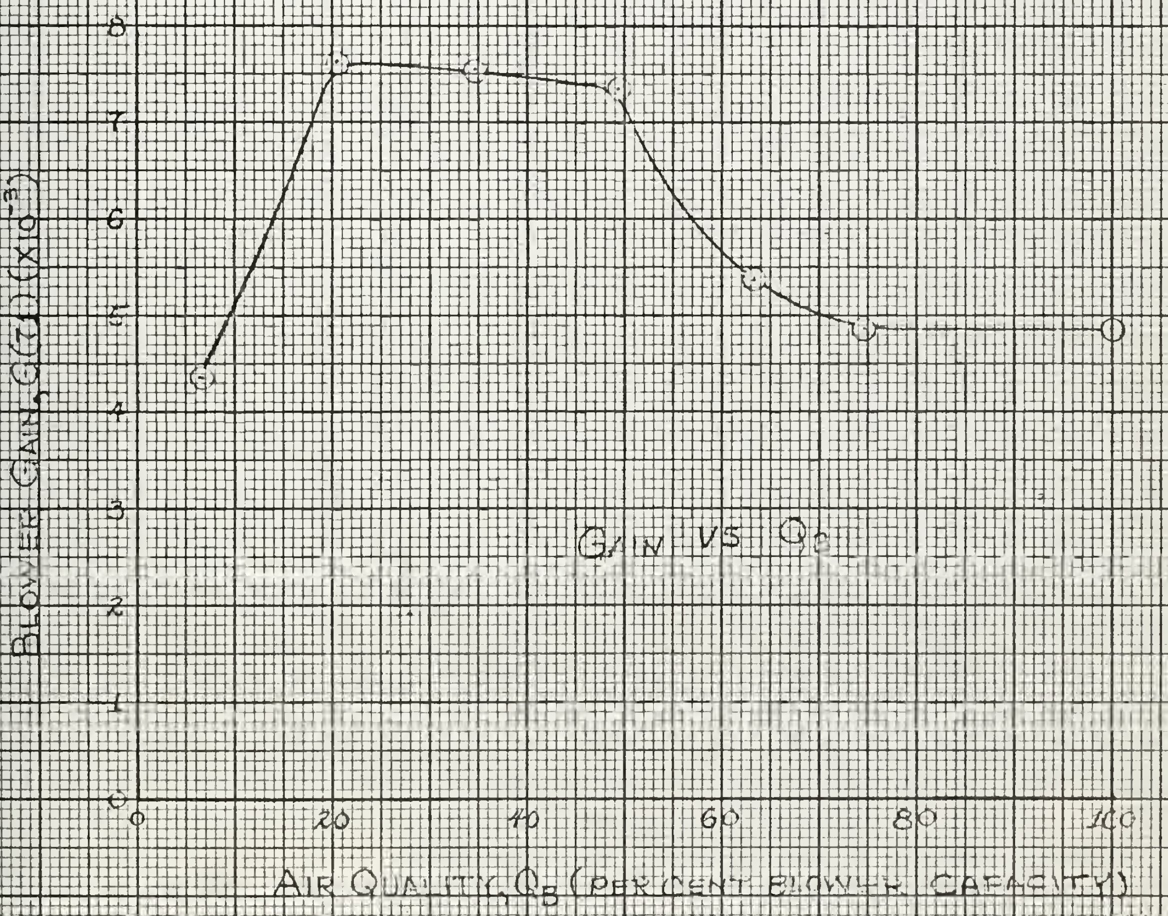


Figure 4-10 Forced Draft Blower Gain vs Air Quality

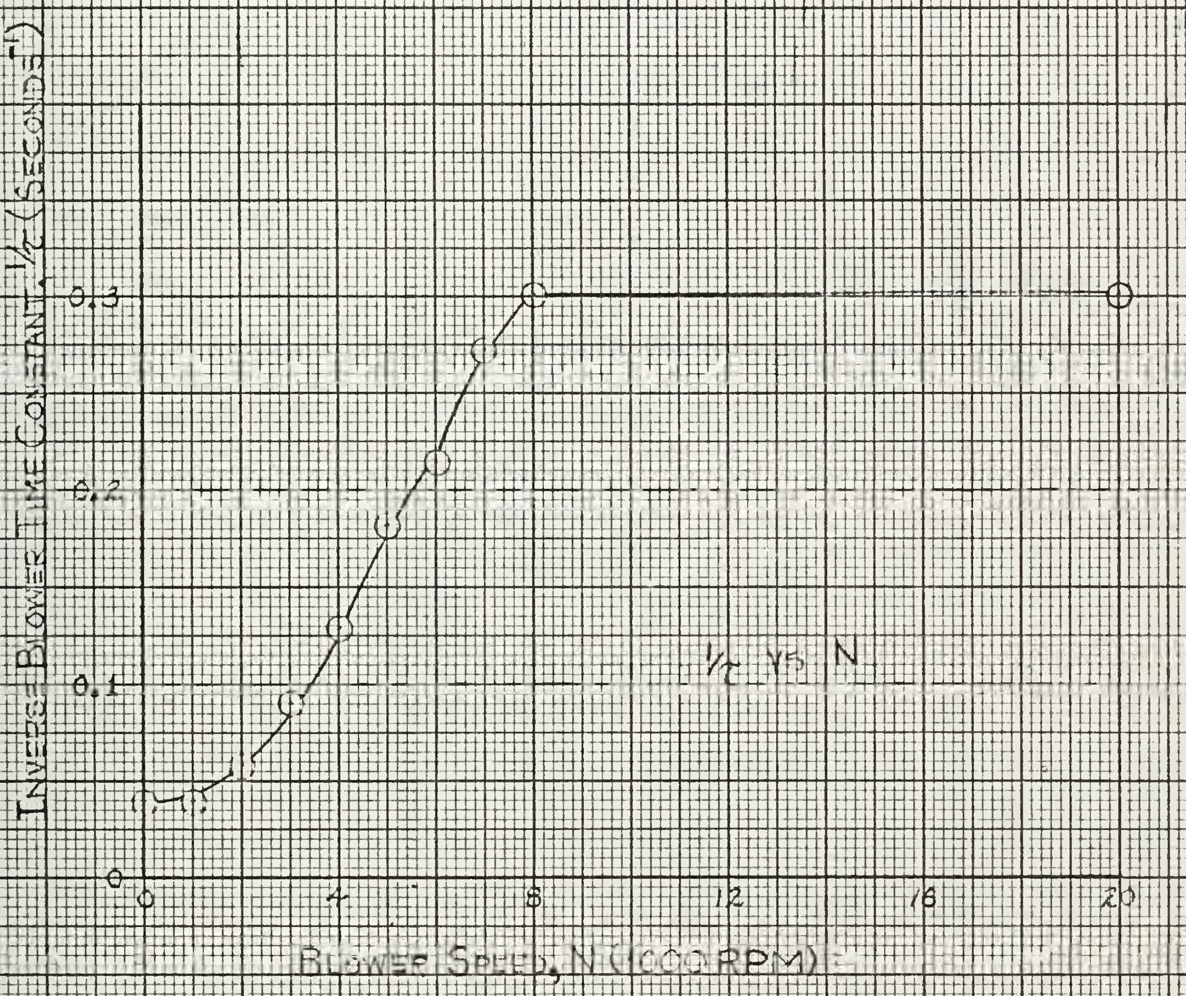


Figure 4-11 Inverse Forced Draft Blower Time Constant vs Forced Draft Blower Speed

bias having a range of plus or minus three psi. The air flow calibrating relay is shown in figure 4-8 with a positive three psi bias applied.

4.8 Root Locus Studies

By means of program Root Locus (Appendix II)root locus studies of the air flow control system were undertaken to determine the relative stability of the system with respect to possible changes in system gain.

Two studies were made. One was at a blower speed of 3000 RPM, which is near the plant's cruising condition; and the other was at a blower speed of 7000 RPM which is near the 90% full power condition. The gain of the system was varied from three tenths of its normal gain to a value of three times its normal gain.

Figure 4-12 is the root locus plot for 3000 RPM. The closed loop system is stable for the normal gain and has roots, which are encircled on figure 4-12, at:

-.1205 +j1.227
-.1205 -j1.227
-.3459 +j0.04162
-.3459 -j0.04162
-.8520
-2.371
-3.981 +j9.201
-3.981 -j9.201

The system is unstable at 1.505 times the normal gain.

Figure 4-13 is the root locus plot for the air system at 7000 RPM. The closed loop system is stable for the normal gain and has roots which are encircled on figure 4-13 at:

-0.1555 +j1.243
-0.1555 -j1.243
-0.7697
-0.4029 +j0.295
-0.4029 -j0.295
-3.929 +j9.176
-2.466
-29.29

The system is unstable at 1.699 times the normal gain.

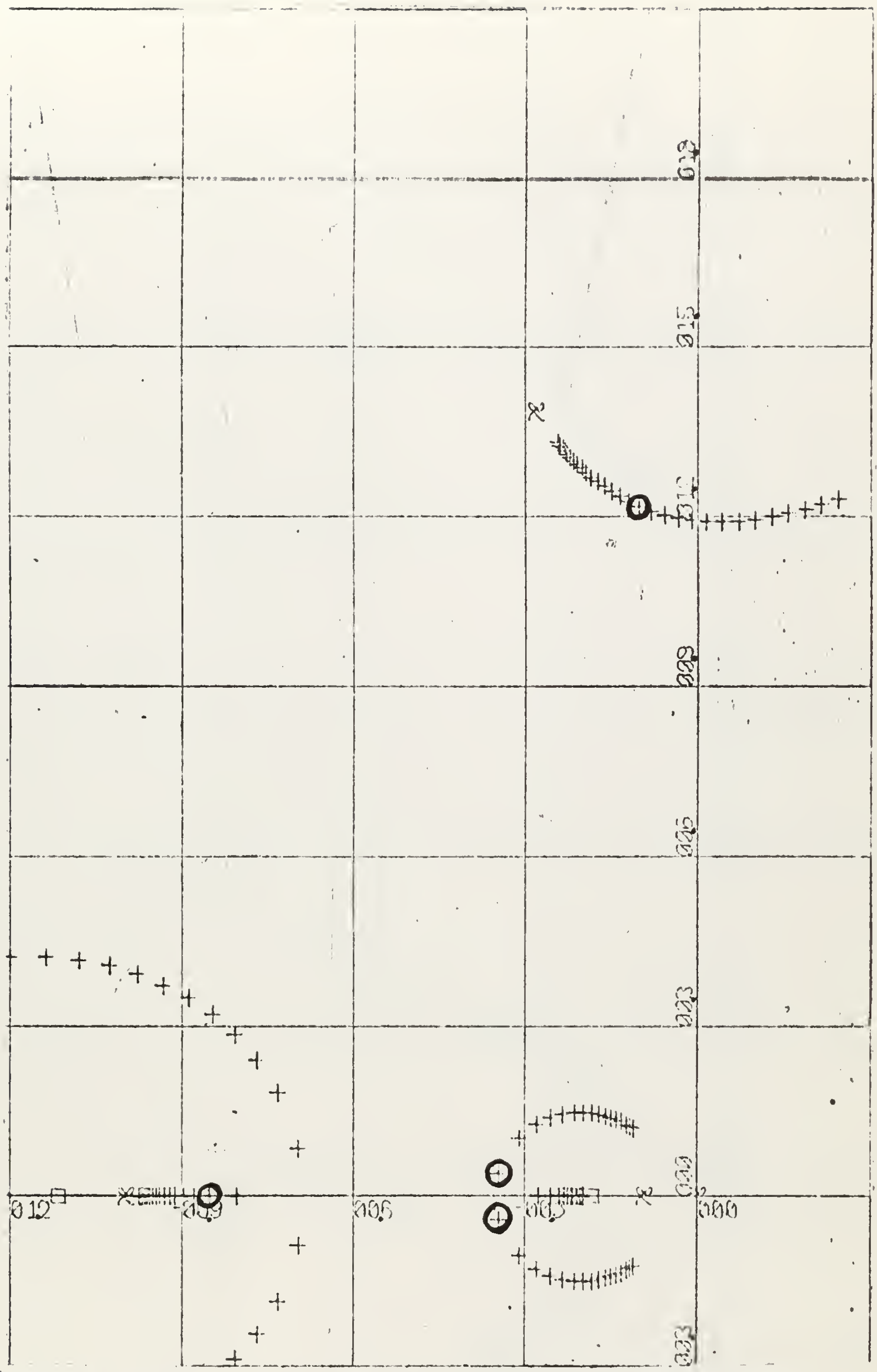


Figure 4-12 - Air system root locus with forced draft blower speed of 3000 RPM.

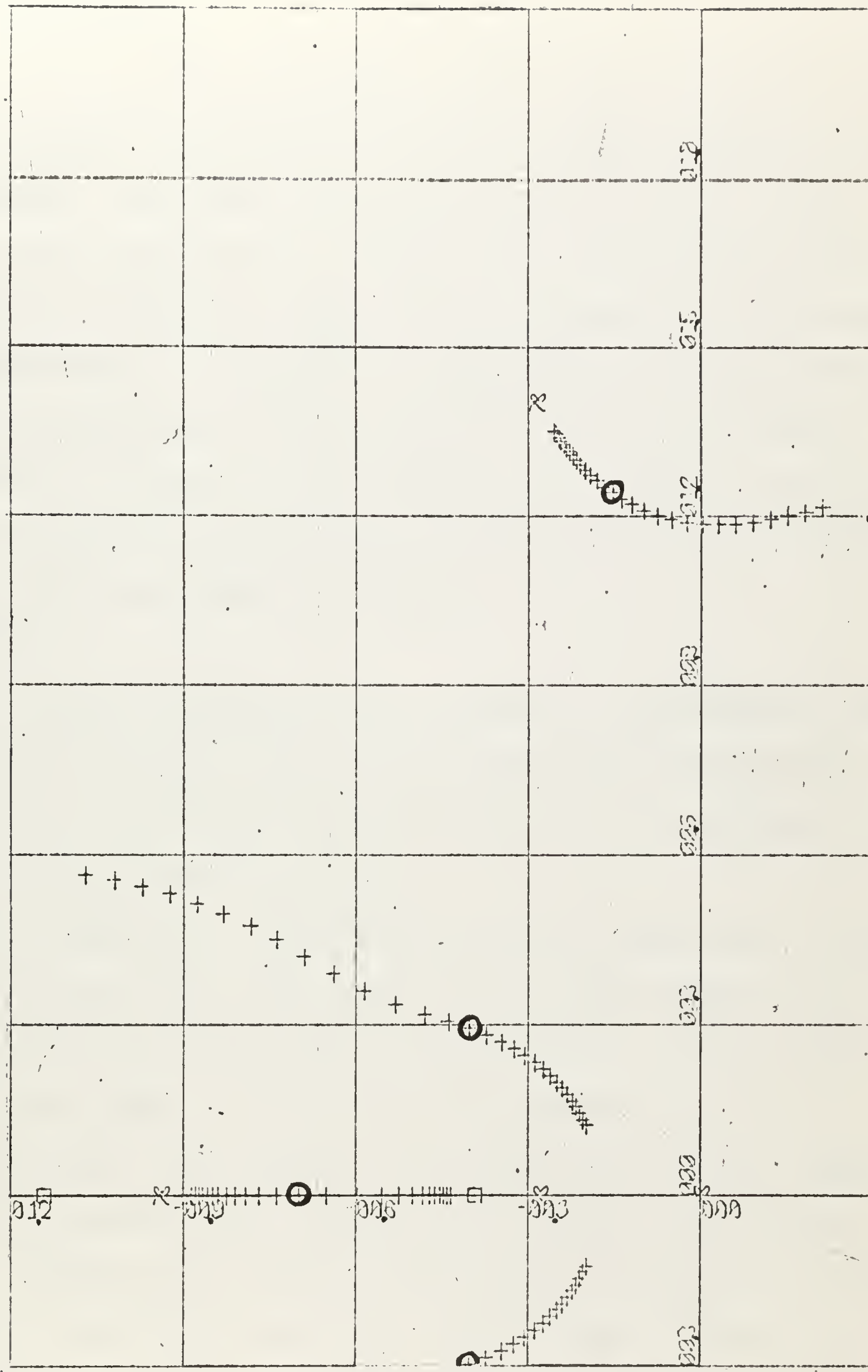


Figure 4-13 - Air system root locus with forced draft blower speed of 7000 RPM.

4.9 Air Flow Control System Simulation

4.91 System Simulation

The air flow control system model is shown in block diagram form in figures 4-3 and 4-8. The model was simulated using program ANALOG on the digital computer. The inputs to the model were steam flow, Gs, and the superheater outlet pressure, Po. The inputs were taken from experimental data furnished by NBTL [4] . Figure 4-14(a) is the graph of the superheater outlet pressure used as an input in the simulation where the steam flow was increased from ten per cent to 90 per cent of full power in 23 seconds. Figure 4-14(b) is the graph of the superheater outlet pressure used as an input in the simulation where the steam flow was decreased from 90 per cent to ten per cent of full power in 23 seconds.

4.92 Results

Figure 4-15(a) is the actual system response to a ramp change in steam flow from the ten per cent to the 90 per cent full power condition in 23 seconds. The peak air flow of 87 per cent occurs at 29.5 seconds and air flow value is 78 per cent at 70 seconds.

Figure 4-15(b) is the response of the model to a ramp change in steam flow from the ten per cent to the 90 per cent full power condition in 23 seconds. The peak air flow occurs at 28 seconds and has a value of 89.4 per cent. The air flow is 77.5 per cent at 70 seconds.

Figure 4-16(a) is the response of the actual system to a ramp change in steam flow from 90 per cent to ten per cent full power in 23 seconds.

Figure 4-16(b) is the response of the model to a ramp change in steam flow from the 90 per cent to the ten per cent full power condition in 23 seconds.

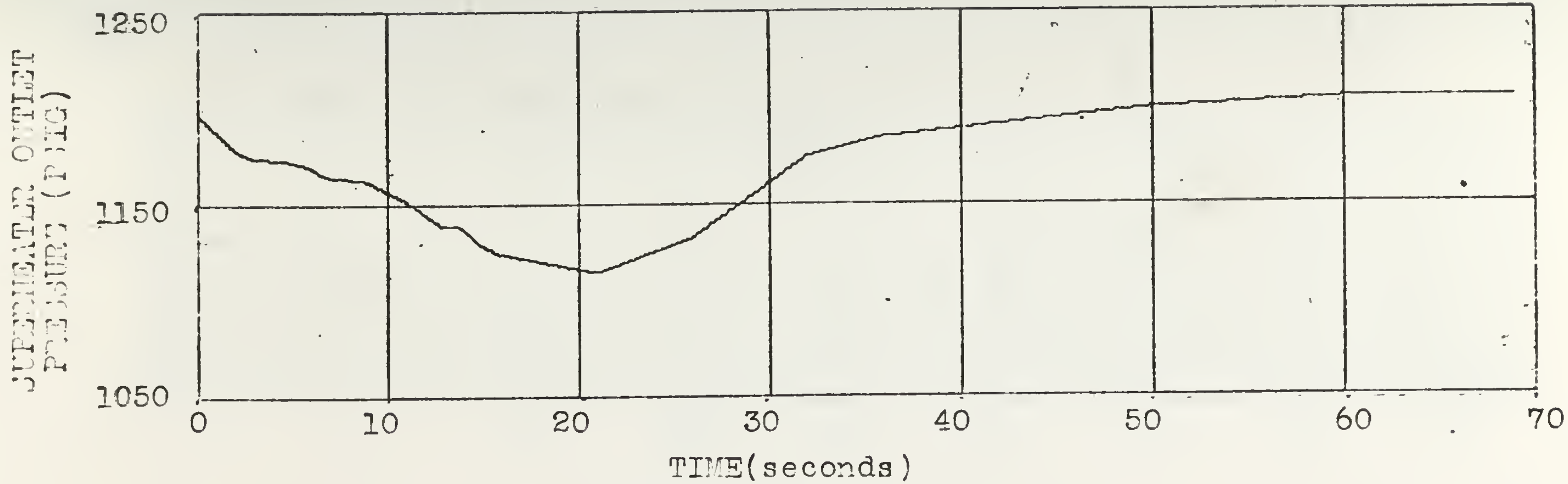


Figure 4-14(a) - SUPERHEATER OUTLET PRESSURE VS TIME

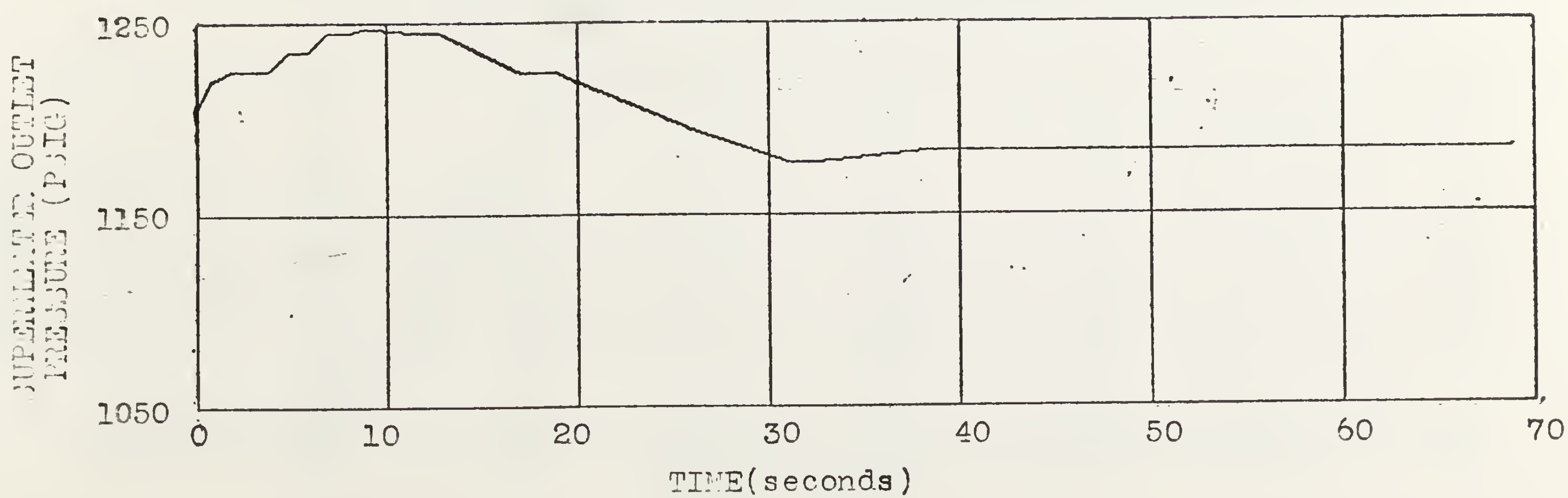


Figure 4-14(b) - SUPERHEATER OUTLET PRESSURE VS TIME

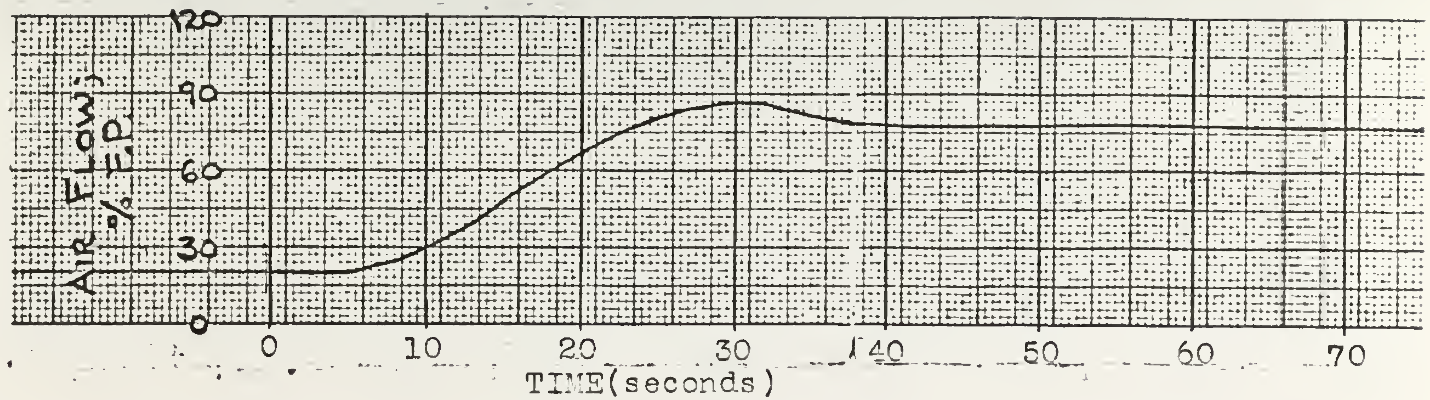


Figure 4-15(a) - AIR FLOW VS TIME for a ramp change in steam flow from 10 to 90 per cent full load in 23 seconds.

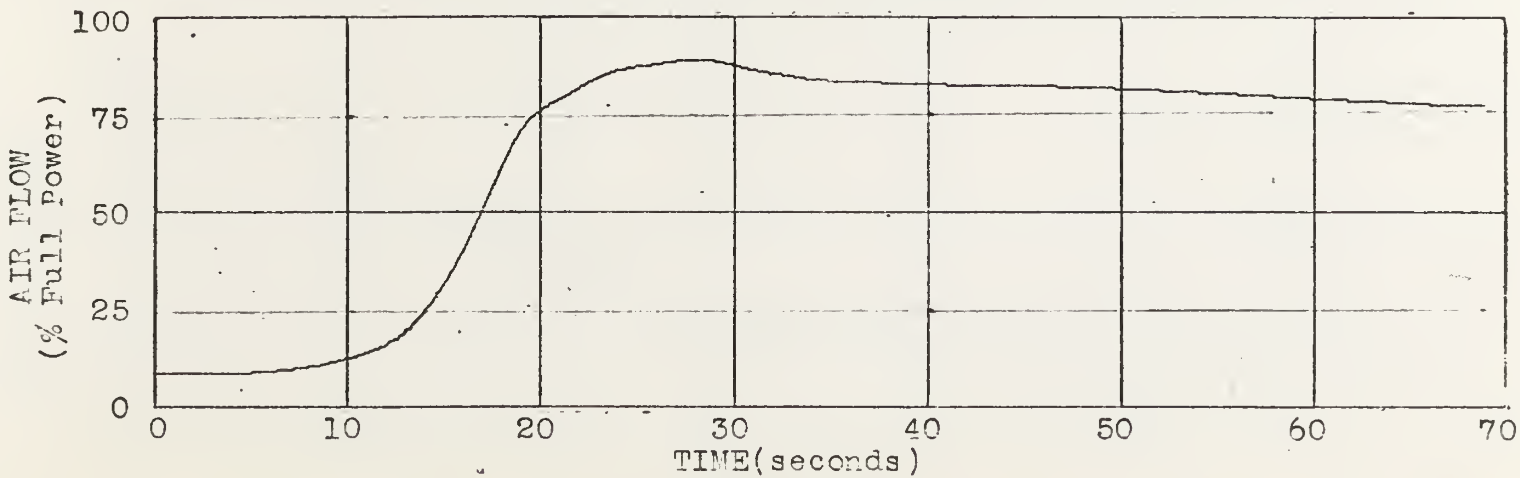


Figure 4-15(b) - AIR FLOW VS TIME for a ramp change in steam flow from 10 to 90 per cent full load in 23 seconds.

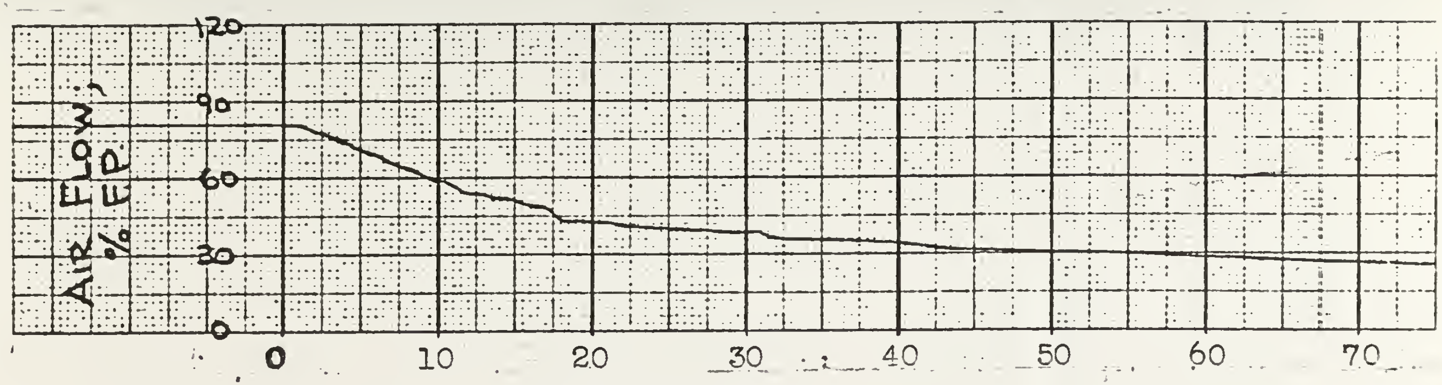


Figure 4-16(a) - AIR FLOW VS TIME for a ramp change in steam flow from 90 to 10 per cent full load in 23 seconds.

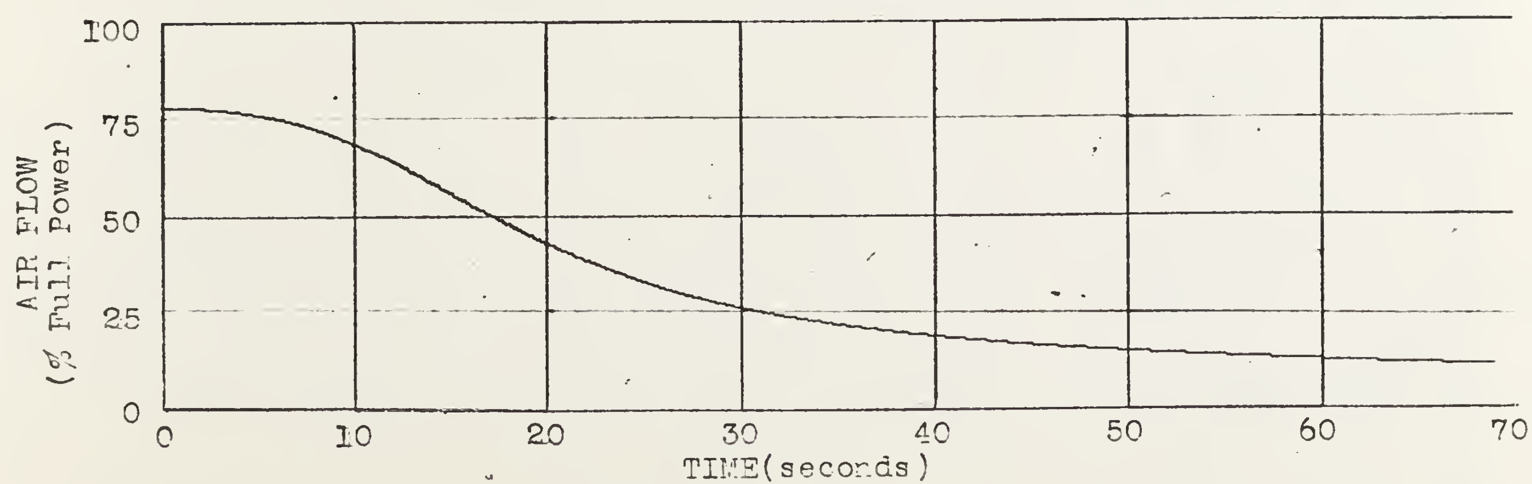


Figure 4-16(b) - AIR FLOW VS TIME for a ramp change in steam flow from 90 to 10 per cent full load in 23 seconds.

4.93 Conclusions

Figures 4-15 and 4-16 show that the simulation model accurately portrays the air flow control system.

There is a difference in the starting points of the actual system and the model due to the superheater outlet pressures at which the tests were started. The model simulations were started with a superheater outlet pressure of 1200 psi while the actual system tests were started at a slightly different superheater outlet pressures. A change of ten psi in the superheater outlet pressure will cause a change of approximately five per cent in the quality of the air.

5. Fuel Oil Flow Control System

5.1 Discussion

The fuel oil flow control system is of the return flow burner type of fuel oil system, which is essentially linear in both static and dynamic characteristics. The system is composed of:

a. Proportional Plus Reset Oil Flow Controller (Bailey Meter Company "Mini-Line" Standatrol)

b. Return Fuel Oil Flow Control Valve (Fisher Governor Company Model YFES-9M)

c. Supply and Return Fuel Flow Transmitters (Bailey Meter Company Model JR-13 Area Meter)

d. Oil Flow Totalizing Relay (Bailey Meter Company "Mini-Line" Relay)

The block diagram is shown in figure 5-1 with pnuematic input signal, Pdf, as the demand index, and the output being the fuel oil flow of the boiler, Gf. There is a constant input of 15,900 lbs/hr of fuel oil supplied to the system at a constant pressure of 1000 psi and the burners are designed to return fuel oil to the fuel oil pump and this amount is determined by the return fuel oil control valve.

5.2 Proportional plus Reset Oil Flow Controller

This Standatrol, like the one in the air flow control system, is a typical proportional plus integral controller. The input pneumatic signal, Pf, is balanced against a pneumatic reference, Pdf, from the fuel limiting selector relay and the Standatrol developes an output air signal, Pdr, which is sent as the control signal to the return fuel oil flow control valve.

5.3 Return Fuel Oil Flow Control Valve

This V-port fuel oil control valve produces linear return fuel flow

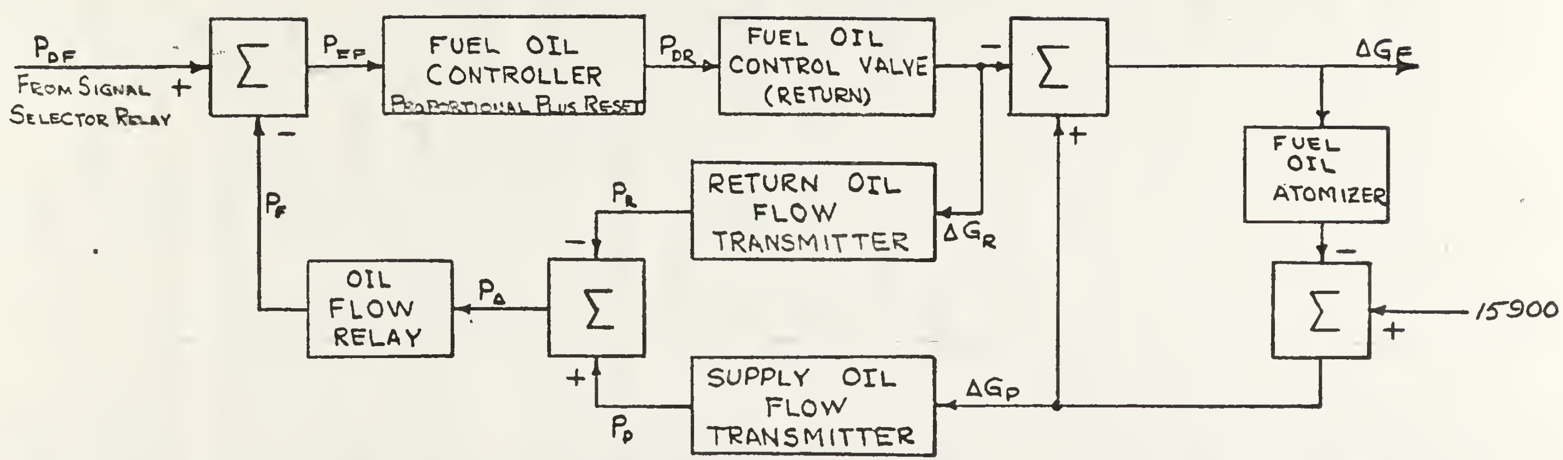


Figure 5-1 Fuel oil flow control system

with lift, and the variation in firing rate of the burner with changes in return fuel flow is linear. This valve is a diaphragm operated valve without positioner. The valve has a pneumatic signal, Pdr, as its loading signal and its output is Δ Gr, the return fuel flow.

5.4 Supply and Return Fuel Flow Transmitter

These area meters measure the supply fuel flow, Δ Gp, and the return fuel flow, Δ Gr, respectively, by means of a metering valve, and each transmits a pneumatic signal, Pr from the return fuel flow transmitter and Pp from the supply fuel flow transmitter, which is representative of the amount of fuel flow. These pneumatic signals are sent to the oil flow relay.

5.5 Oil Flow Totalizing Relay

This relay develops an output pneumatic pressure, Pf, that is linearly proportional to the flow of fuel oil burned. This signal is obtained by subtracting the return fuel oil pneumatic signal, Pr, from the supply fuel oil pneumatic signal, Pp. This signal, Pf, which represents the fuel oil burned, is transmitted to the oil flow Standatrol and is balanced against the oil demand signal, Pdf, from the fuel limiting relay.

5.6 Stability Analysis of the Fuel Oil Control System

5.61 Discussion of the Problem

The first computer test runs which were conducted using the transfer functions for the fuel oil control system furnished by NBTL [1] showed that the fuel oil control system was unstable. This, in turn, caused the simulation of the complete boiler to be unstable.

5.62 Root Locus Study of Fuel Oil Control System

In order to prove that the fuel oil system alone made the complete boiler simulation unstable with the data furnished, a root locus of the system was derived from figure 5-2. Since

$$Gf = Gp - Gr \qquad 5.1$$

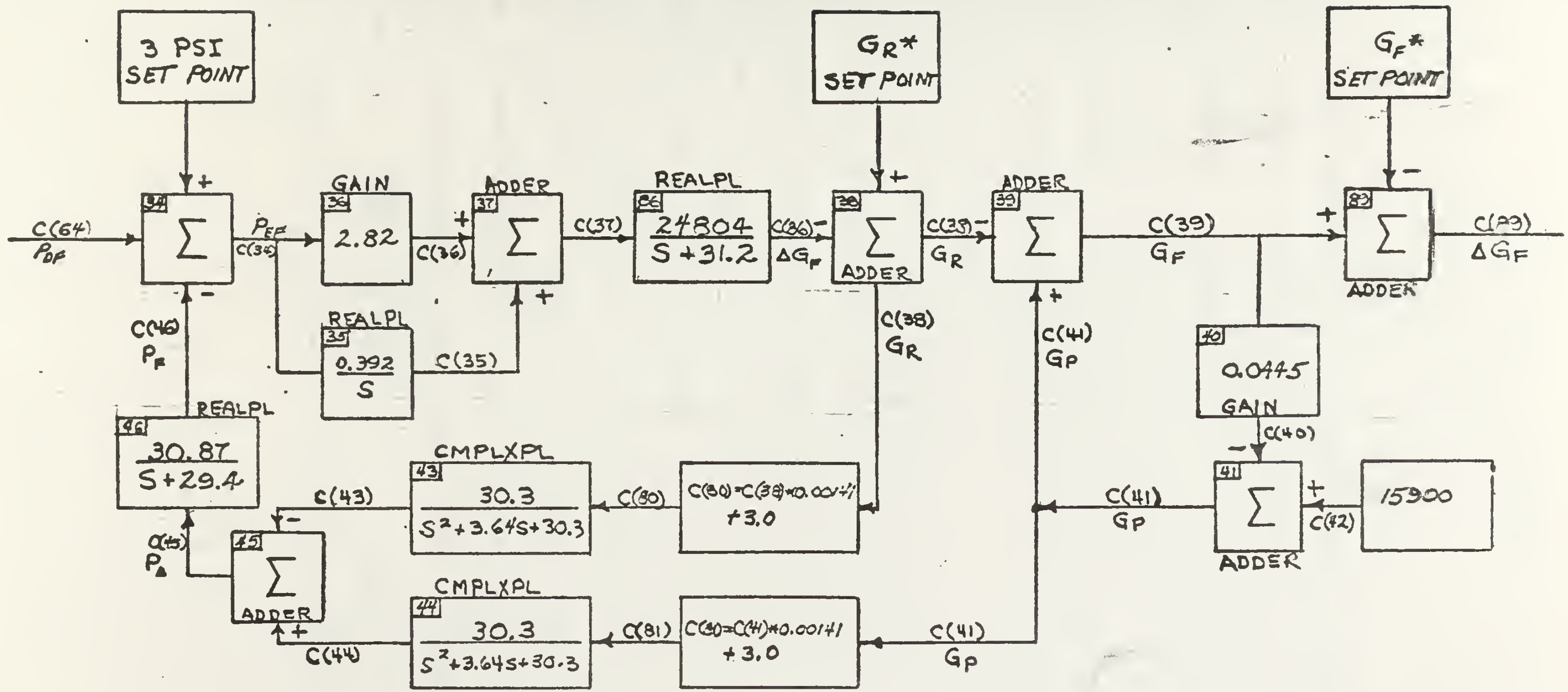


Figure 5-2 Program Analog simulation of fuel oil flow control system

Gf could be fed thru the feedback loop in stead of Gp - Gr. Also, from figure 5-2

$$Gp = 15{,}900 - .0445\ Gf \tag{5.2}$$

Adding equations 5.1 and 5.2 yields

$$1.0445\ Gf = 15{,}900 - Gr \tag{5.3}$$

Using the above manipulations, figure 5-2 can be reduced to figure 5-3 in order to produce a characteristic equation for a root locus plot. The root locus of the system, figure 5-3, is shown in figure 5-4. The gain of the system is varied from three tenths to three times the gain of the system as shown. From this root locus it is seen that the system is unstable for the specified gain with a pair of complex roots in the right half plane at $+.67 \pm j10.0$.

5.63 Supply and Return Oil Transmitter's Dynamics

The transient response to a step input test which was conducted at NBTL [1] on the area meter transmitter is shown in figure 5-5. The transfer function of the transmitter's dynamics was simulated on an analog computer and the transient response to a step input is shown in figure 5-6(a). This response did not compare favorably with the actual test response, figure 5-5. By adjusting the damping coefficient of the quadratic term on the analog computer, a more favorable response was attained (figure 5-6(b)). The second order approximation of the dynamics of the transmitter was found to be $\dfrac{1}{.033s^2 + 0.195s + 1}$. A comparison of the responses shown in figures 5-5, 5-6(a), and 5-6(b) are tabulated in table 5-1.

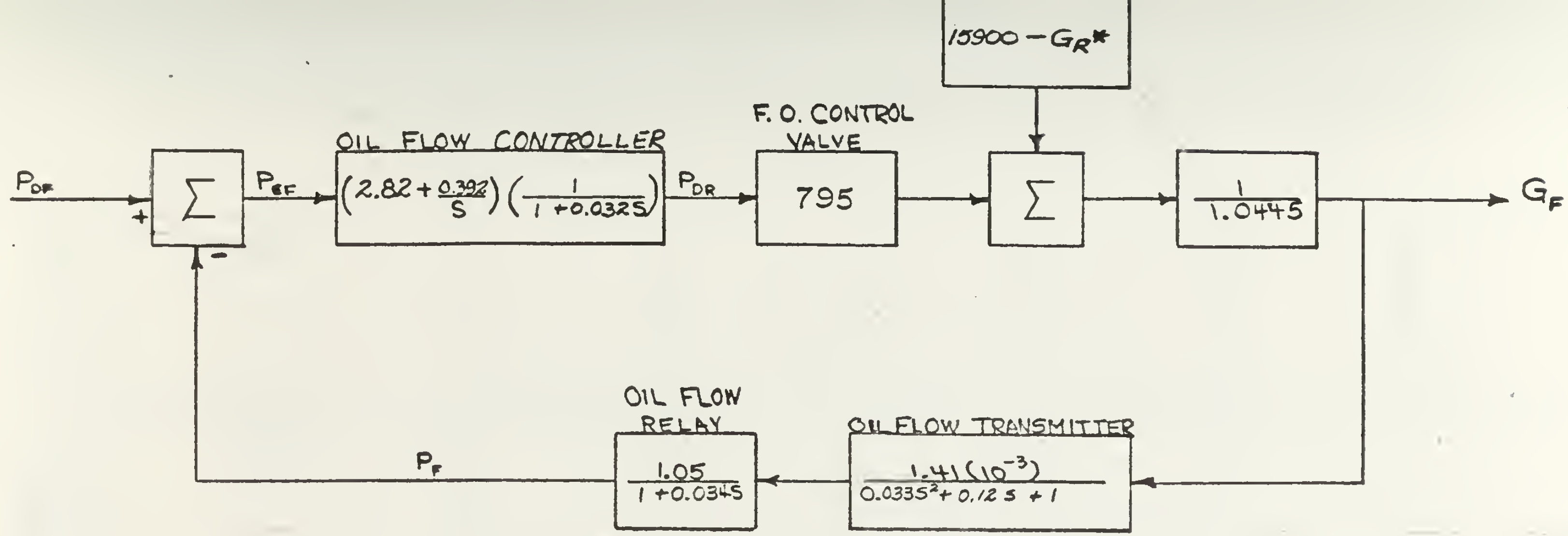


Figure 5-3 Fuel oil flow control system block diagram for root locus studies

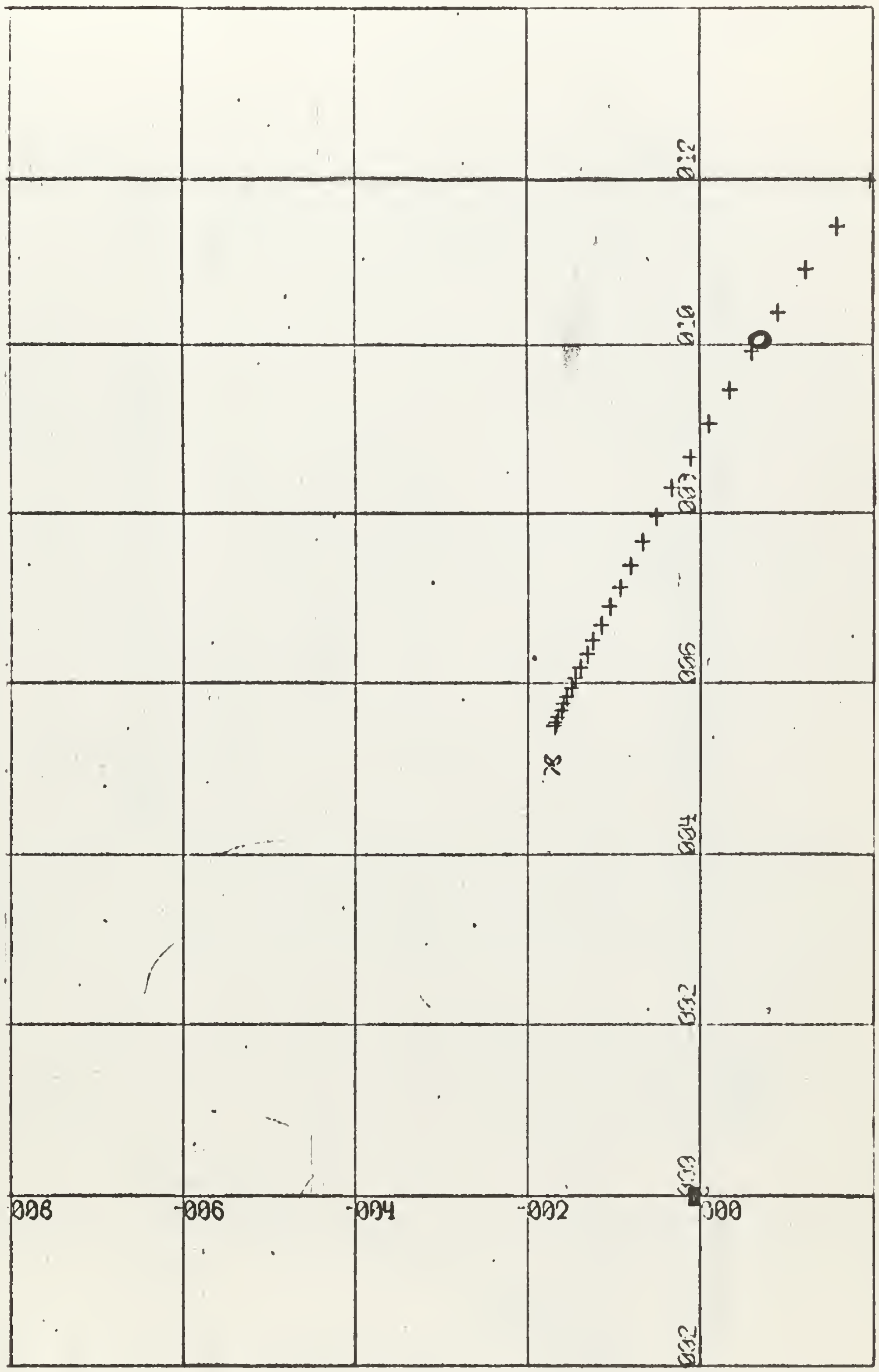


Figure 5-4 - Fuel oil control system root locus with transmitter dynamics furnished by NBTL.

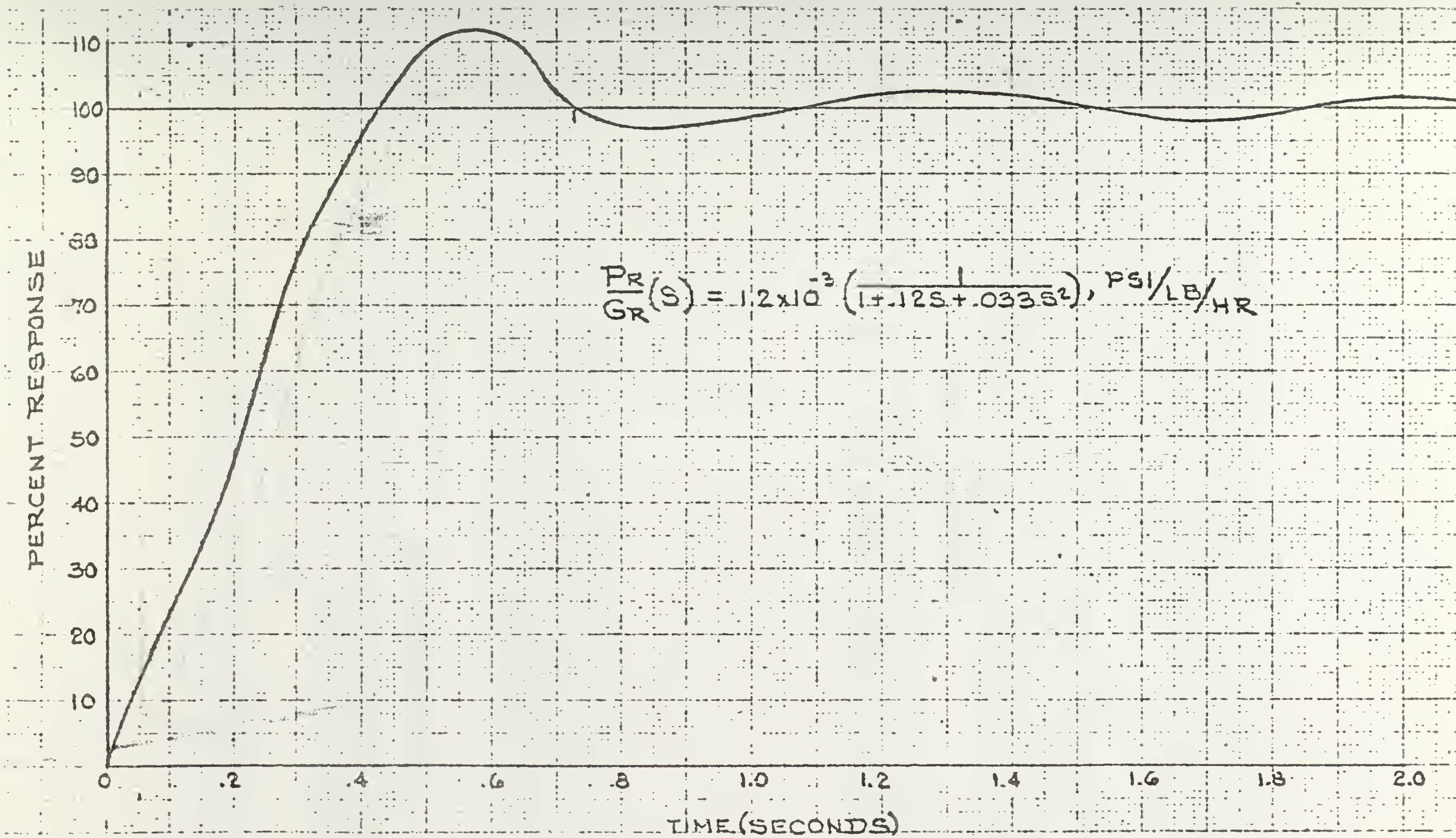


Figure 5-5 - Area meter transmitter transient response to a step input.

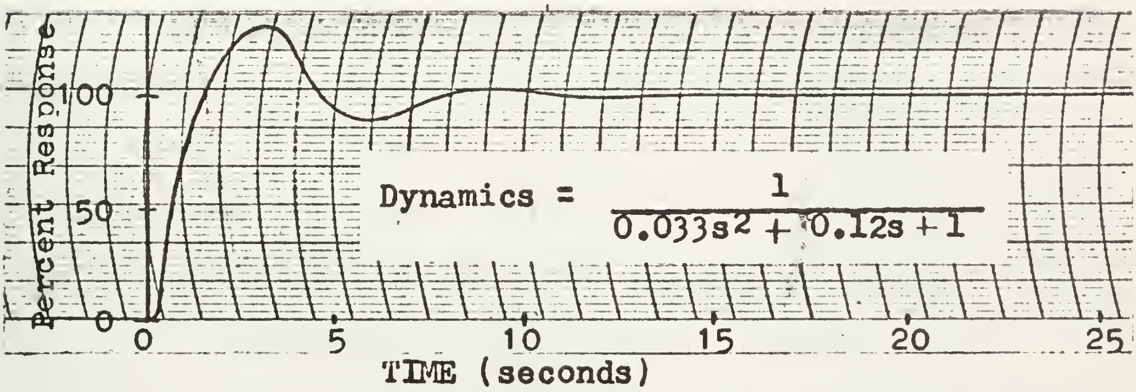


Figure 5-6(a) - Area meter transmitter transient response to a step input - Analog computer simulation.

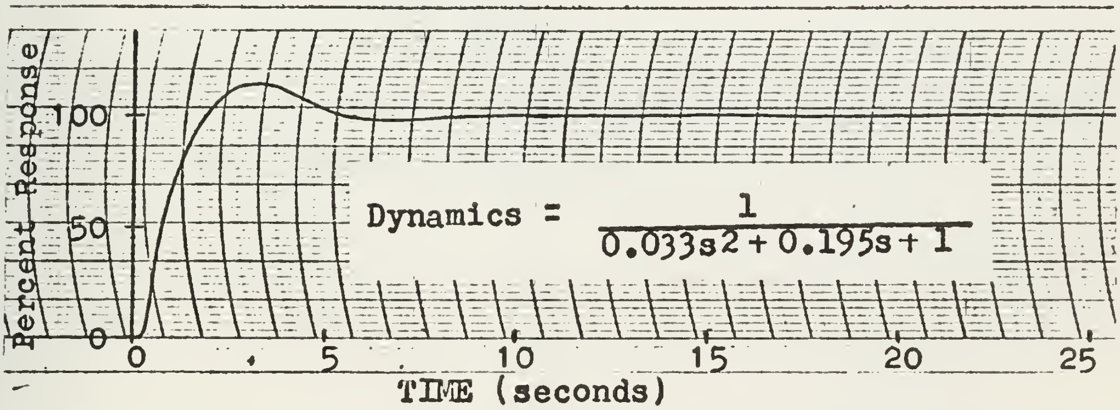


Figure 5-6(b) - Area meter transmitter transient response to a step input - Analog computer simulation.

TABLE 5-1

Figure	5-5	5-6(a)	5-6(b)
Dynamic Transfer Function		$\frac{1}{.033s^2 + .12s + 1}$	$\frac{1}{.033s^2 + .195s + 1}$
Rise Time (100%)	.43 sec	.38 sec	.46 sec
Max Overshoot	12%	31%	13.5%
Time to peak	.55 sec	.6 sec	.6 sec
Second Crossover	.73 sec	1.0 sec	1.1 sec

This table illustrates why this set of dynamics was chosen.

5.64 Root Locus Results with New Transmitter Dynamics

Using the new value in the dynamics for the supply and return oil transmitters, the root locus of this system was plotted and is shown in figure 5-7. Again a range of gains from three tenths of normal gain to three times that gain is plotted. For the system at its specified gain the closed loop system is stable with the following roots:

$$\begin{array}{l} -.1065 \\ -.25 \pm j9.9 \\ -33. \pm j8.8 \end{array}$$

The closed loop system is somewhat oscillatory because of the complex roots at $-.25 \pm j9.9$, but it is not dominated by these roots.

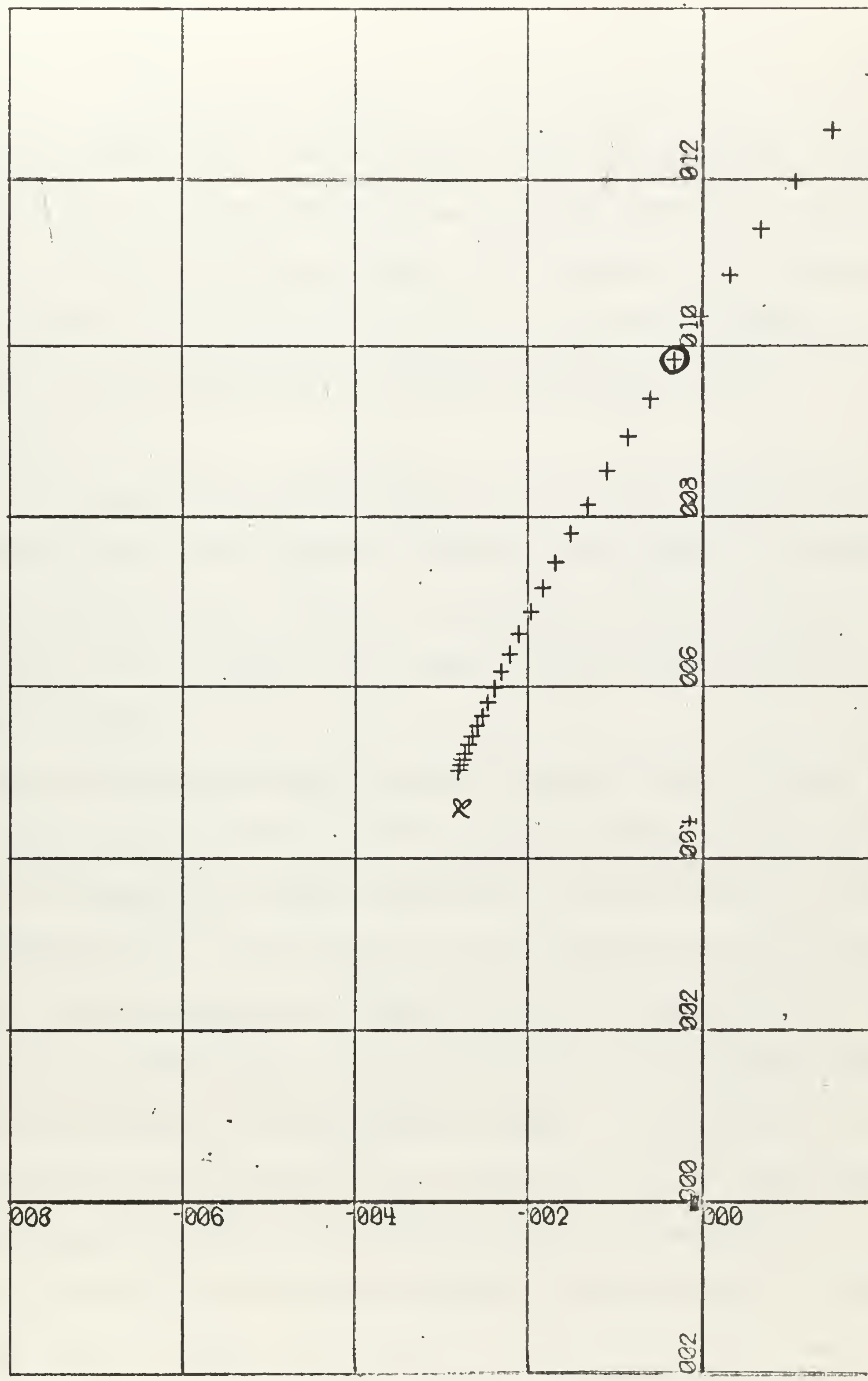


Figure 5-7 - Fuel oil control system root locus with transmitter dynamics determined by analog computer results.

5.7 Fuel Oil Flow Control System Simulation

5.71 System Simulation

The fuel oil flow control system is shown in block diagram for program Analog in figure 5-8. This system was tested and simulated in conjunction with the air flow control system, since these two are connected by the fuel oil limiting selector relay, and the inputs to the combined air flow and fuel oil systems are steam flow, Gs, and the superheater outlet pressure, Po, as was discussed previously in section 4.91.

5.72 Results

The system response to a ramp change of ten to 90 per cent full power in steam flow from a test conducted on the DLG-9 test boiler at NBTL [4] is shown in figure 5-9(a). For this test the fuel oil flow reached a peak of 107% of fuel oil flow at full power (13,000 lbs/hr), and the final value was 87%.

The results from the digital computer simulation shown in figure 5-9(b) indicate a peak of 95.6% in 30 seconds and a final value of 87%. The test data from NBTL is somewhat questionable since the fuel oil flow does not follow the air flow response as stipulated by the fuel oil limiting relay. As was previously discussed, the fuel oil limiting relay transmits the fuel oil demand signal, which is the lower of two signals from the air flow system and the master demand signal. If the fuel oil flow were as indicated in figure 5-9(a) that is, leading the air flow, black smoke would issue from the boiler due to excessive firing of the burners.

Figure 5-10(a) illustrates the response of the test boiler at NBTL [4] for a ramp change in steam flow from 90 to ten per cent of full power. In this test the fuel oil has a minimum value of 18% at 22 seconds and settles out to a final value of 25%.

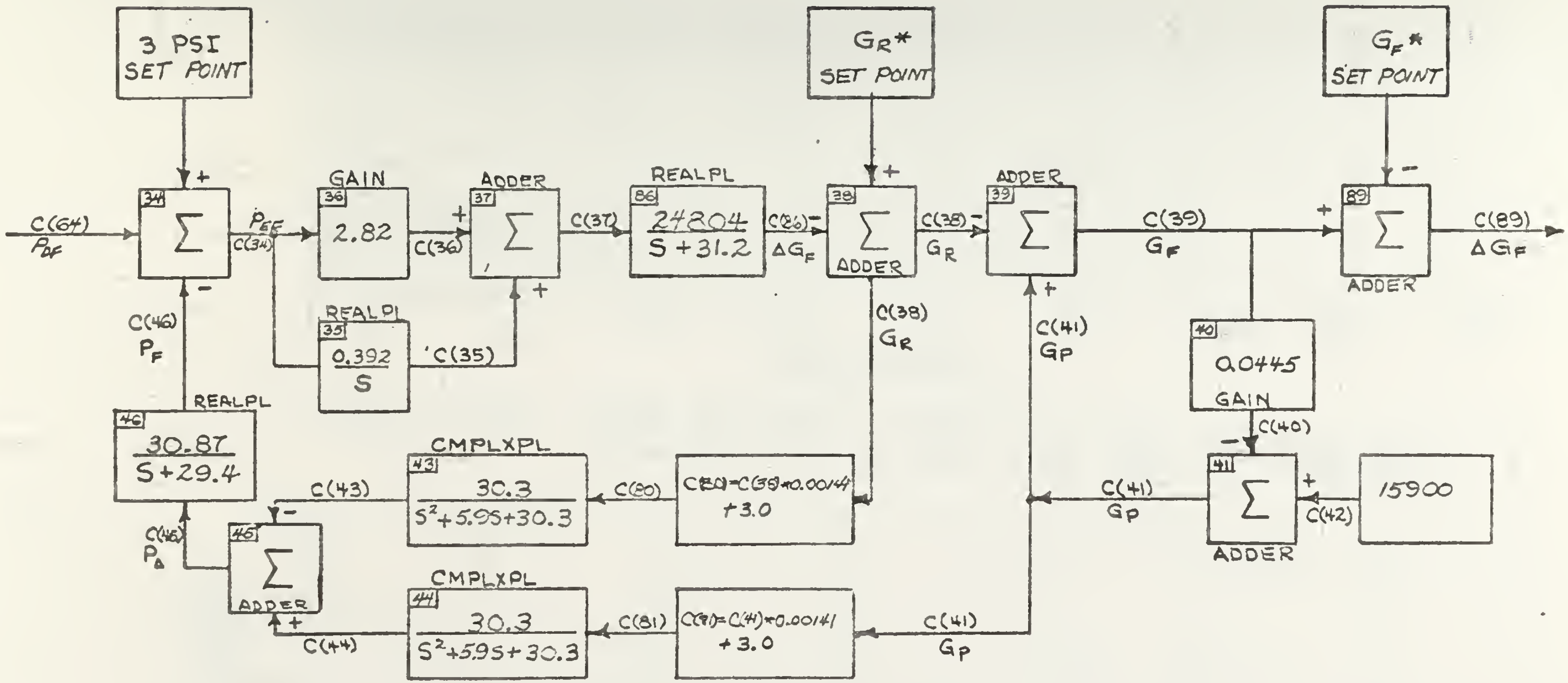


Figure 5-8 Program Analog simulation of fuel oil control system with corrected transmitter dynamics

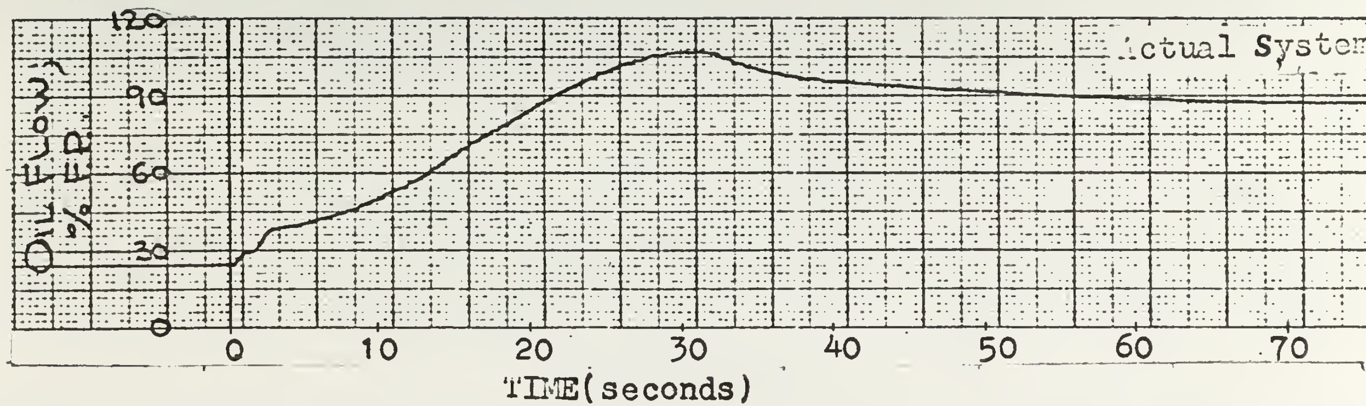


Figure 5-9(a) - FUEL OIL FLOW VS TIME for a ramp change in steam flow from 10 to 90 per cent full load in 23 seconds.

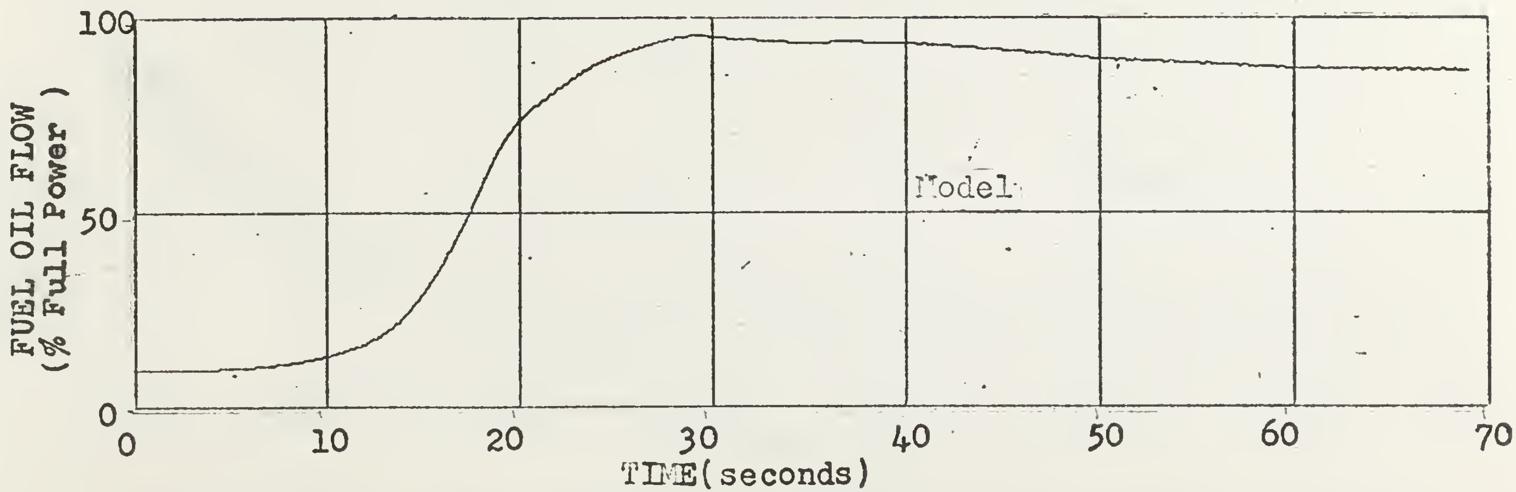


Figure 5-9(b) - FUEL OIL FLOW VS TIME for a ramp change in steam flow from 10 to 90 per cent full load in 23 seconds.

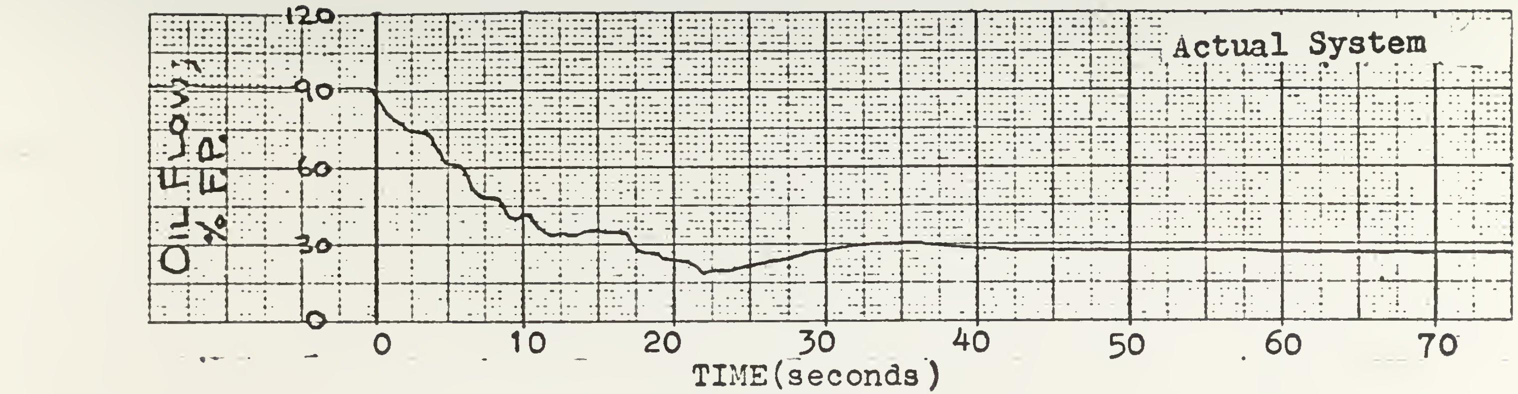


Figure 5-10(a) - FUEL OIL FLOW VS TIME for a ramp change in steam flow from 90 to 10 per cent full load in 23 seconds.

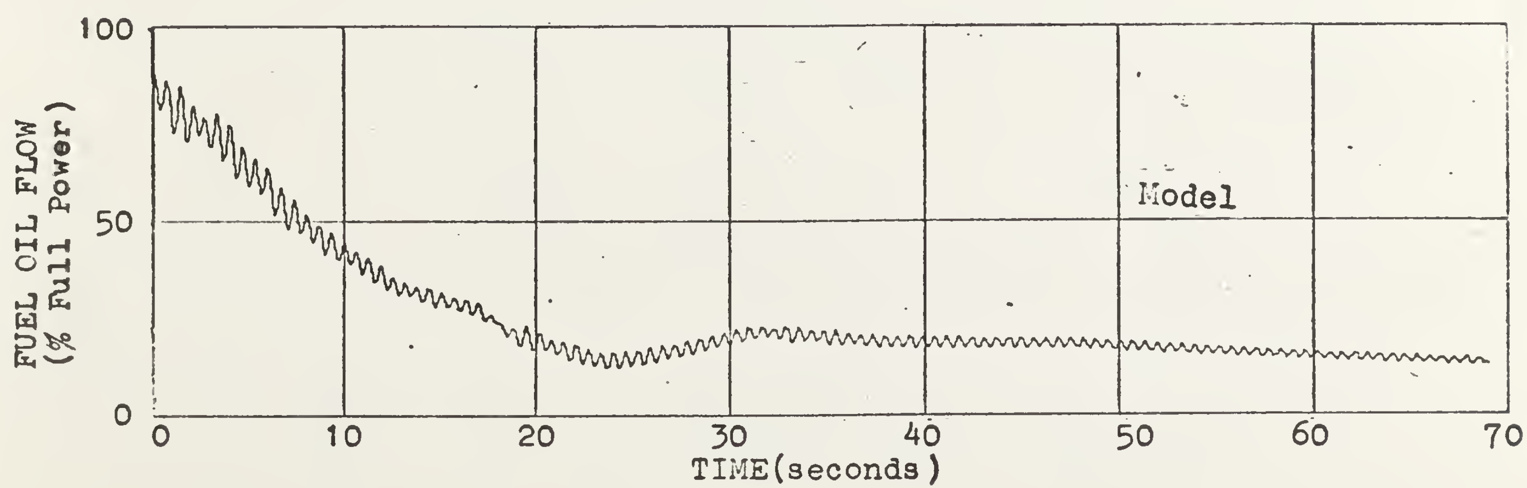


Figure 5-10(b) - FUEL OIL FLOW VS TIME for a ramp change in steam flow from 90 to 10 per cent full load in 23 seconds.

The digital computer simulation results, presented in figure 5-10(b) has a minimum value of 15% at 22 seconds and has a final value of 14%.

6. Boiler Water Level Control System

6.1 Discussion

The water level in the boiler steam drum is regulated by a conventional three-element feedwater control system. The system is designed in cascade fashion; that is, the proportional plus reset control mode regulates feedwater flow rate to equal steam flow rate while simultaneously maintaining boiler drum water level at the desired value. This arrangement is programmed to produce a smooth transient response which to some degree compensates for variations in feedwater flow rate caused by the effects of "shrink" and "swell" when changing load. The system consists of:

a. Proportional Plus Reset Drum Water Level Controller (Bailey Meter Company "Mini-Line" Standatrol).

b. Feedwater Control Valve (Bailey Meter Company Model A-FFD-1B)

c. Water Flow Transmitter and Steam Flow Transmitter. (Bailey Meter Company Model CR-166).

d. Water Flow Feedback Signal Filter (Bailey Meter Company Needle Valve Volume Chamber Assembly).

e. Drum Water Level Transmitter (Bailey Meter Company Model IS43X).

f. Steam Flow-Water Flow Differential Relay (Bailey Meter Company "Mini-Line" Relay).

This system is arranged as shown in figure 6-1 with the pneumatic signal, Pgs, corresponding to steam flow as the demand index, the pneumatic signal Pl, representing the boiler drum water level as the supervisory signal and the water flow, Δ Gw, as the output of the system.

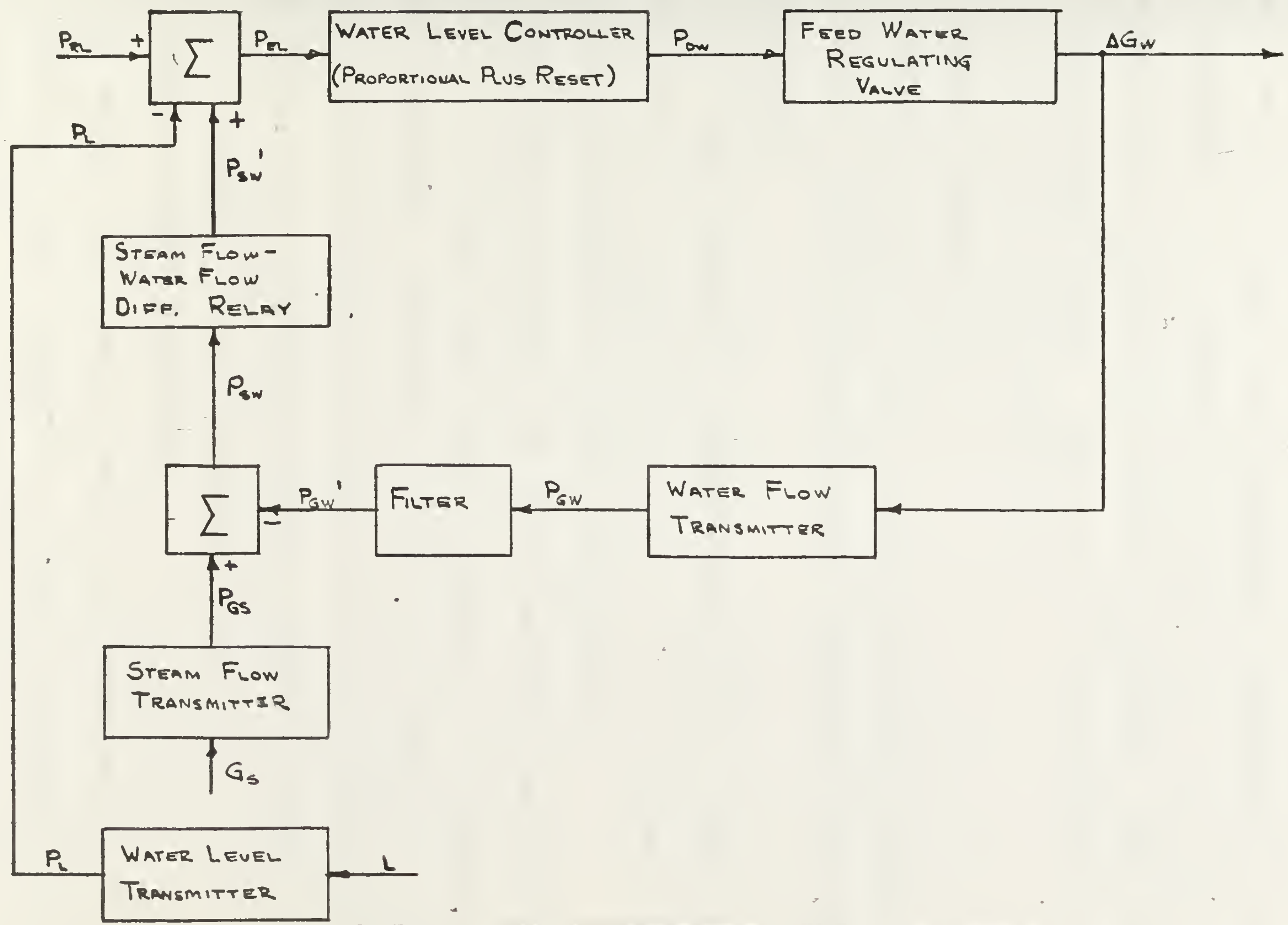


Figure 6-1 Feedwater level control system

6.2 Proportional Plus Reset Drum Water Level Controller

This Standatrol differs from the ones in the air flow and the fuel flow systems in as much as this is a three element controller in which the reference pneumatic signal, Prl, is compared with the pneumatic signal, Pbw', from the steam flow - water flow differential relay, and Pl, which is sent from the drum water level transmitter, and generates a pneumatic error signal, Pel. This pneumatic error signal, Pel, acts as the loading pressure for the Standatrol which transmitts a pneumatic signal, Pdw, to the feedwater regulating valve. The action of this Standatrol is typical of an integral plus proportional controller.

6.3 Feedwater Control Valve

This control valve is a typical V-ported positioner equipped diaphragm control valve, which has the characteristic underdamped second order frequency response.

The pneumatic signal, Pdw, from the water level controller acts as the loading signal for the valve and the output is Gw, the feedwater flow.

6.4 Water Flow Transmitter and Steam Flow Transmitter

Both of these transmitters are of the same design, and the following description of the water flow transmitter applies to the steam flow transmitter. The pressure differential related to the feedwater flow, Gw, is measured across an orifice and the square root of this differential pressure is extracted, thus the transmitter develops a pneumatic loading pressure Pgw, which is proportional to the feedwater flow.

6.5 Water Flow Feedback Signal Filter

This needle valve-volume tank serves the function of an R-C filter in the feedback path which is designed to attenuate the feedwater control system response, Pgw, to the high frequency components in the measured water flow signal, Pgs.

6.6 Drum Water Level Transmitter

The water level transmitter is a bellows type inverse acting differential pressure transmitter. It is designed to measure and transmit differential head pressure between water level in the boiler drum and a reference column of condensate connected into the steam space above the water level in the steam drum; the steady state calibration curve changes one psig (Pl) for each one inch of boiler level change (Δ L). The pneumatic output of the water level transmitter, Pl, is sent to the water level controller as described in section 6.2.

6.7 Steam Flow - Water Flow Differential Relay

This relay subtracts the pneumatic output from the feedwater flow transmitter, which has been attenuated through the water flow filter, Pgw' from the pneumatic signal, Pgs from the steam flow transmitter and develops an output pneumatic pressure Psw' which is linearly proportional to this difference in pressure. This pneumatic pressure, Psw', is sent to the water level controller as described in section 6.2.

6.8 Stability Analysis of the Water Flow System

6.81 Discussion of the Problem

The first digital computer test runs with the water system isolated, using inputs recorded in test runs by NBTL [4] indicated that the description of the system by the transfer functions determined was somewhat oscillatory. These results led to root locus studies of the system.

6.82 Root Locus Studies of the Water Flow Control System

The water level and water flow control systems are completely interconnected and the feedback of the water flow system is such that a complete root locus study could not be made. Therefore, the effect of the steam flow with the water level input held constant was the locus studied. This

root locus is shown in figure 6-2. For the parameters of the actual system, shown in figure 6-3, the location of the closed roots of the system are:

$$
\begin{array}{r}
-.076 \pm j.75 \\
-.042 \\
-.4 \\
-1.32 \pm j4.18 \\
-.405 \pm j1.16 \\
-29.5
\end{array}
$$

Even though the pair of complex roots at $-.076 \pm j.75$ are not the dominant pair of roots because of the root located at $-.042$, this pair is highly oscillatory and are the probable cause of the oscillation in the feedwater responses for the tests conducted on the digital computer. This complex pair stems from the feedwater regulating valve and the real root at $-.042$ is from the water level controller.

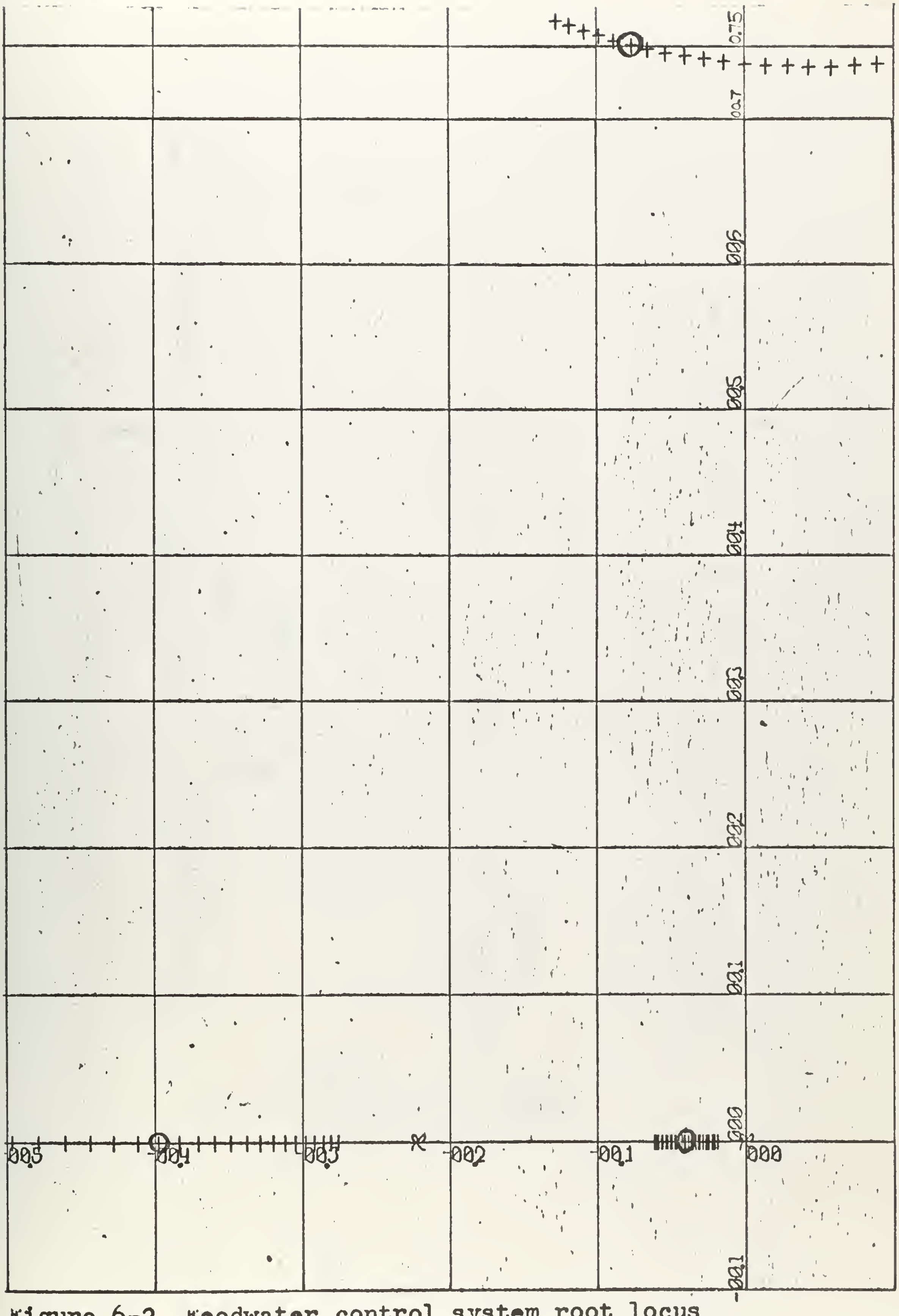


Figure 6-2 Feedwater control system root locus

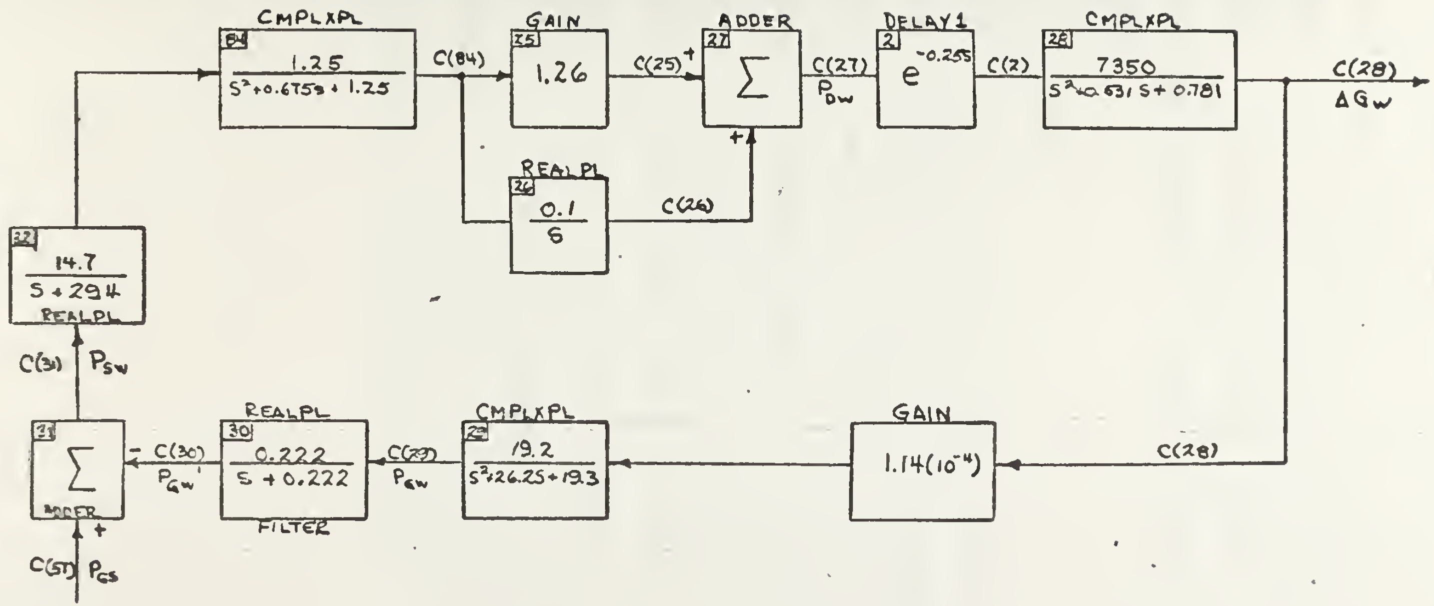


Figure 6-3 Feedwater flow control system with drum water level held constant for root locus study

6.9 Feedwater Flow Control System Simulation

6.91 System Simulation

The feedwater flow control system is shown in block diagram for Program Analog in figure 6-4. This system was tested and simulated independently with data furnished by NBTL [4] . The inputs to the system are steam flow and water level as shown in figures 6-5(a) and 6-5(b) as a result of maneuvering the boiler from ten to 90 per cent full power in 23 seconds.

6.92 Results

The results as shown in figure 6-6(b) indicate that the system as simulated is oscillatory for the first 50 seconds and does not agree with the test data as shown in figure 6-6(a). The oscillations are due to the root locations of the complex pair at $-.076 \pm j.75$ as discussed in section 6.82. It appears that this transient response is superimposed on the response caused by the water level controller and after the initial oscillations died out the water flow closely followed the test results. Without recourse to the actual test equipment, further study of the parameters of this system was not possible and the authors feel that further tests should be conducted on this part of the system.

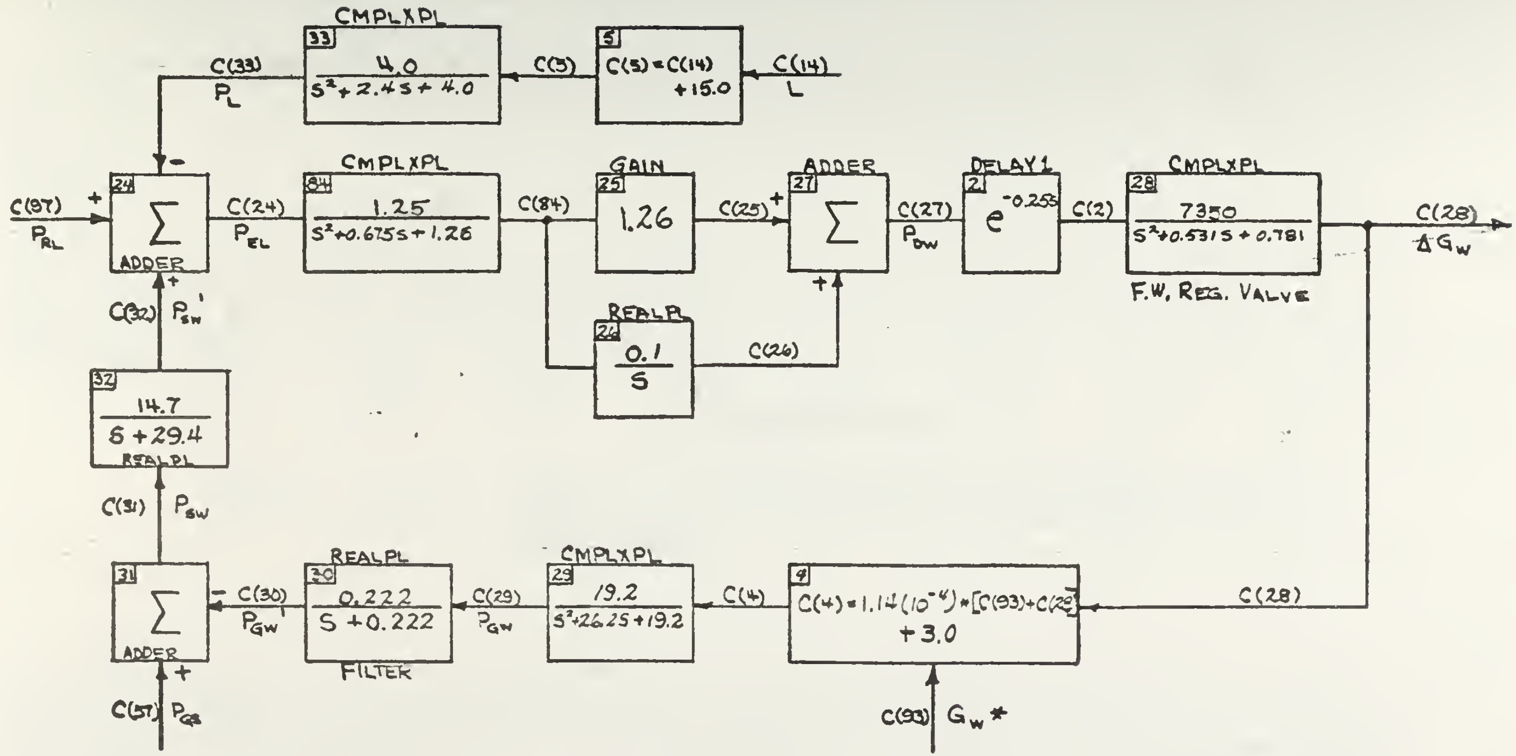


Figure 6-4 Program Analog simulation of feedwater flow control system

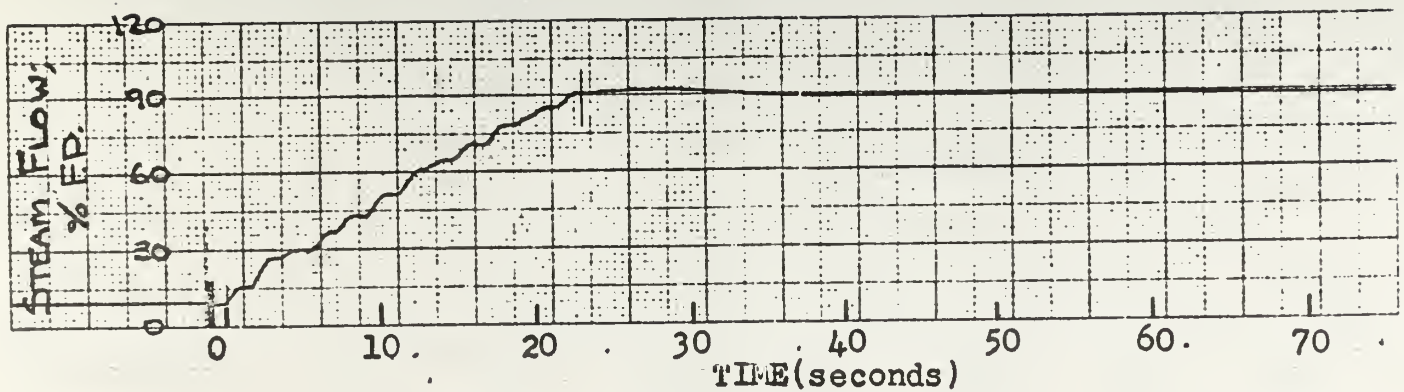


Figure 6-5(a) - STEAM FLOW VS TIME for maneuvering a DLG-9 boiler from 10 to 90 per cent full power in 23 seconds.

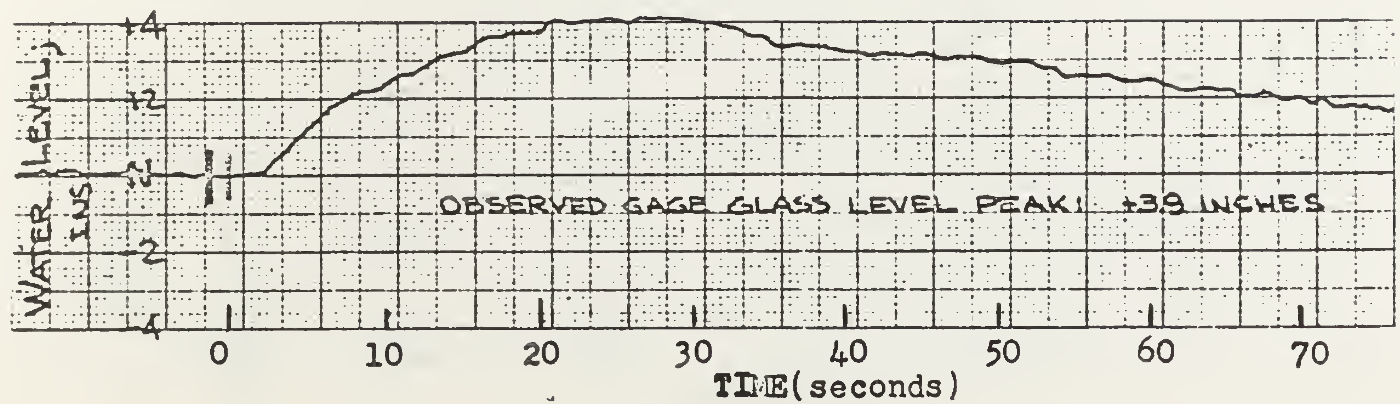


Figure 6-5(b) - WATER LEVEL VS TIME for maneuvering a DLG-9 boiler from 10 to 90 per cent full power in 23 seconds.

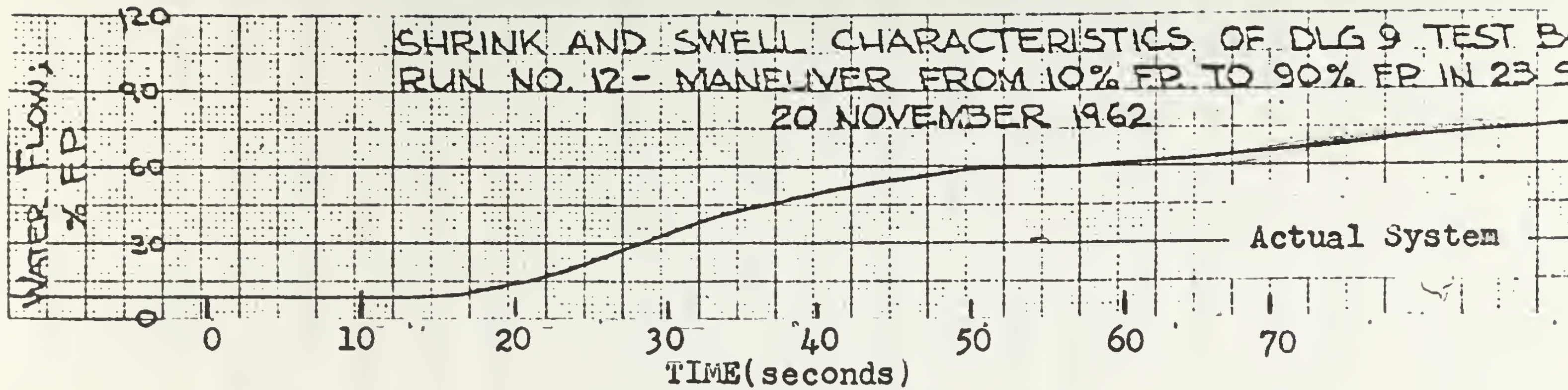


Figure 6-6(a) - WATER FLOW VS TIME for maneuvering a DLG-9 boiler from 10 to 90 per cent full power in 23 seconds.

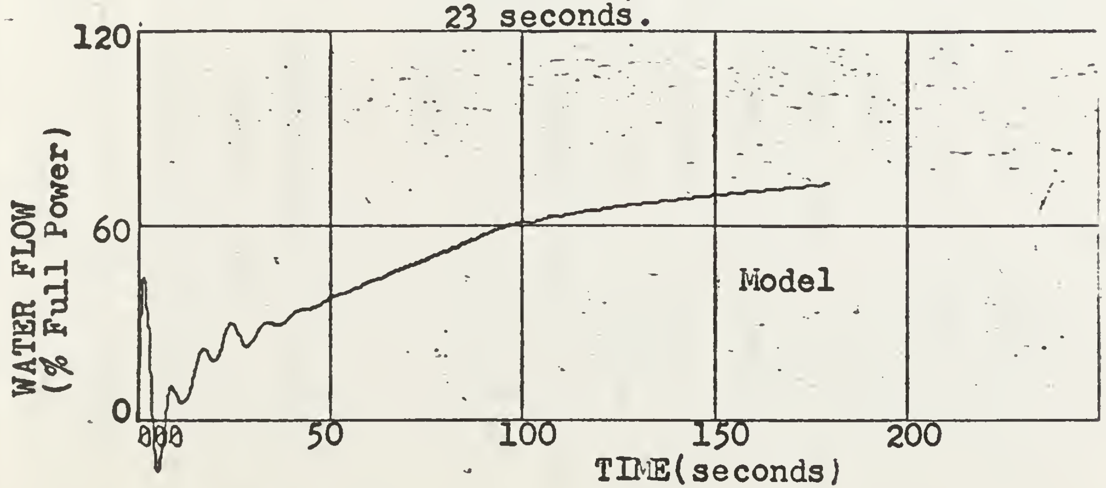


Figure 6-6(b) - WATER FLOW VS TIME for maneuvering a DLG-9 boiler from 10 to 90 per cent full power in 23 seconds.

7. Computer Simulation of the Complete DLG-9 Steam Generator

7.1 Discussion

The complete steam generator, which is composed of the combustion air flow control system, the fuel oil flow control system, the feedwater flow control system, and the boiler transfer functions is illustrated in block diagram form in figure 7-1. This system as shown is in a "delta system" form as received from NBTL [1]. The entire steam generator system was investigated in the following manner. First the system was simulated employing the transfer functions as given for the cruising conditions and a small ramp input was used to perturbate the system; next this same procedure was used with the 90 per cent full power transfer functions. The air flow control system was then changed from the linear condition with two operating points to the non-linear combustion air flow system as analyzed in section 4 and shown in figures 4-3 and 4-8. The entire plant was maneuvered from ten per cent full power to 90 per cent full power using first the cruising condition transfer functions for the boiler and then using the boiler's 90 per cent full power transfer functions. Finally the authors attempted to develop non-linear transfer functions for the boiler based on the ones given at cruising conditions and at 90 per cent full power conditions as a function of steam flow.

7.2 Delta System Simulation

The steam generator system was simulated under two separate conditions using the transfer functions given for cruising conditions and 90 per cent full power respectively. These were appropriately employed in the forced draft blowers and actuators, and in the various boiler transfer functions for the steam pressure and water level; the remaining associated equipment was simulated as described in the preceding sections. The system was

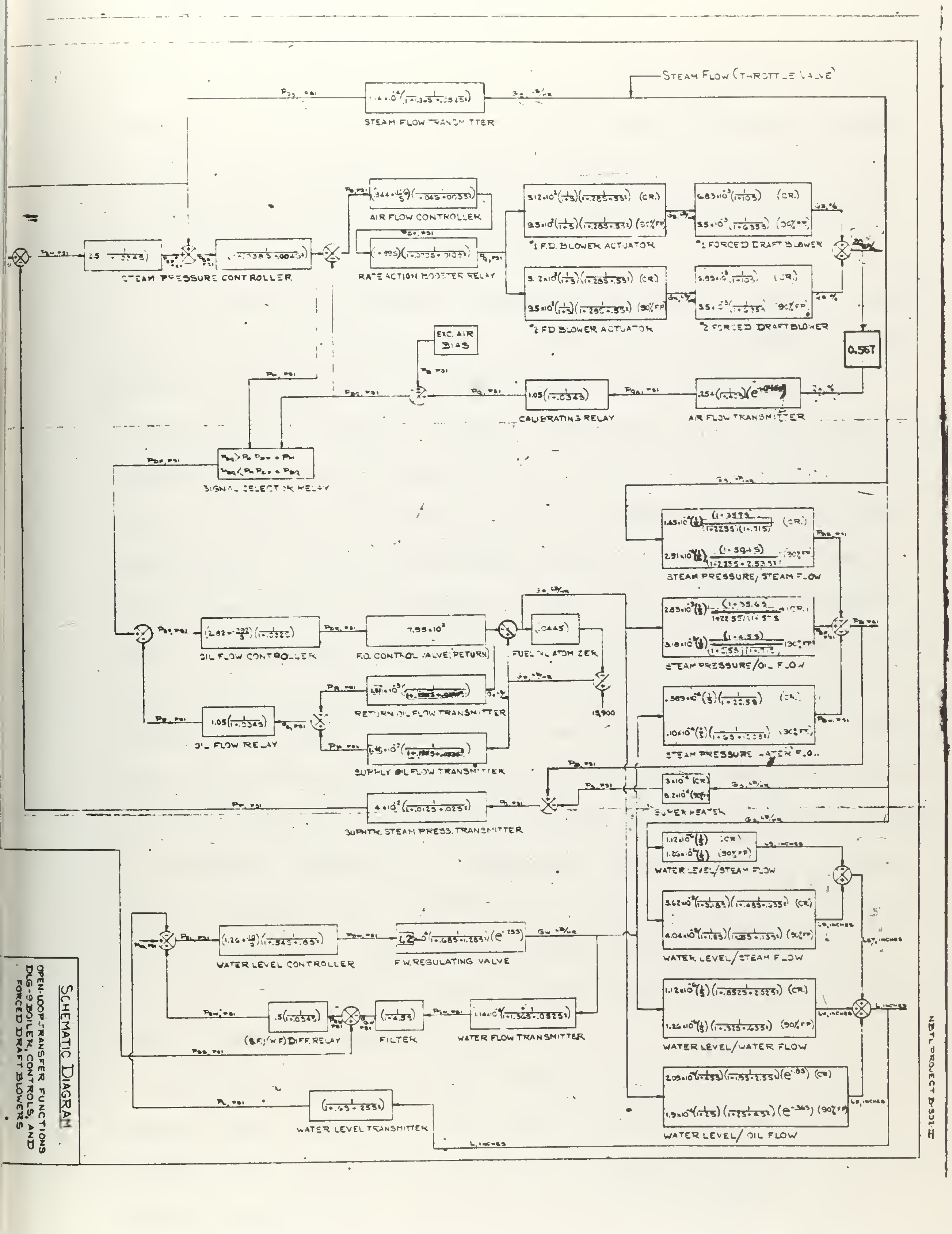


Figure 7- Block diagram of DLG-9 steam generator system

simulated using program Analog which was described in section 2. The subroutine INVAL was the same for both situations and is presented in Appendix III. This subroutine as described in section 2.3 is used to set up the appropriate initial conditions on the various blocks of the system.

7.21 Delta System at Cruising Conditions

The subroutine DIAGRAM and the data for the cruising condition simulation is presented in Appendix III. The steam flow is ramped from cruising conditions (56,000 lbs/hr) to 59,000 lbs/hr in five seconds and held at this value for 50 seconds as shown in figure 7-2(a). The delta water level response to this positive ramp is shown in figure 7-2(b); the peak of .18 inches is reached in 20 seconds and the level approaches the steady state value of zero. The delta steam pressure given in figure 7-3(a) shows a dip in steam pressure of a maximum 3.75 psig at 11.5 seconds as expected, and the steam pressure approaches a zero steady state value. The air flow, figure 7-3(b), exhibits the type of performance one expects for a small change in steam flow. The delta fuel flow, given in figure 7-4(a), showed some slight oscillations as the delta fuel flow approached its final value of 180 lbs/hr. Figure 7-4(b) shows the delta feedwater flow and this system as explained in section 6.92 is oscillatory; also the system is inherently slow and its final value of 3000 lbs/hr is not reached during the duration of this computer run. These results agreed favorably with what was expected from actual boiler operation; however there was no test data available with which to compare the responses.

The delta system at cruising conditions was also perturbed with a negative ramp in steam flow from cruising conditions (56,000 lbs/hr) to 53,000 lbs/hr in five seconds and held at 53,000 lbs/hr for 50 seconds as shown in figure 7-5(a). The delta drum water level response reaches a minimum value of -.18 inches at 12 seconds and then slowly approaches

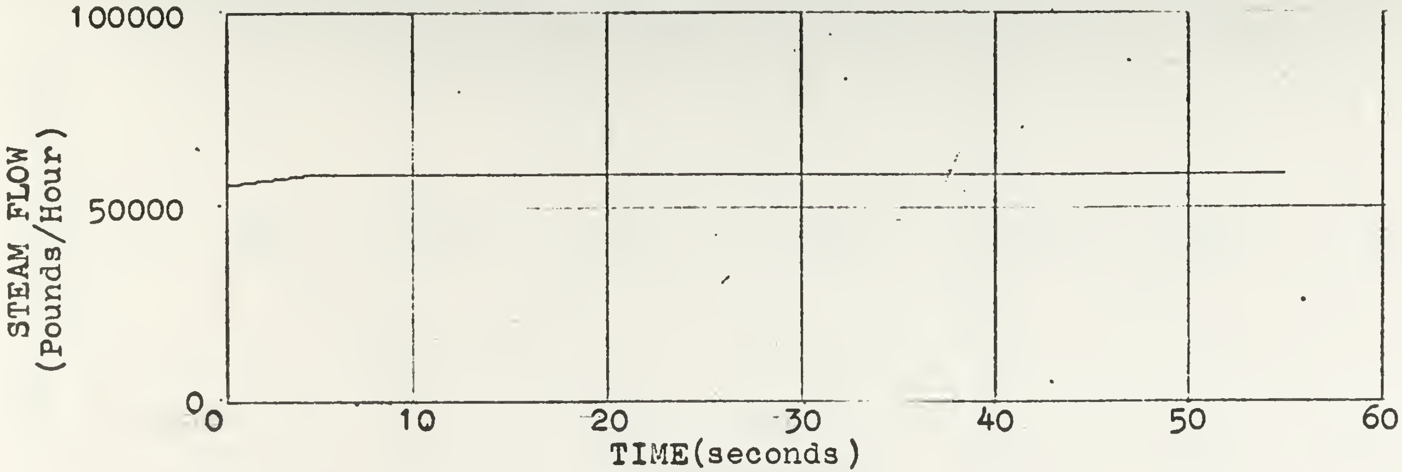


Figure 7-2(a) - STEAM FLOW VS TIME for delta system at cruising conditions with positive ramp applied.

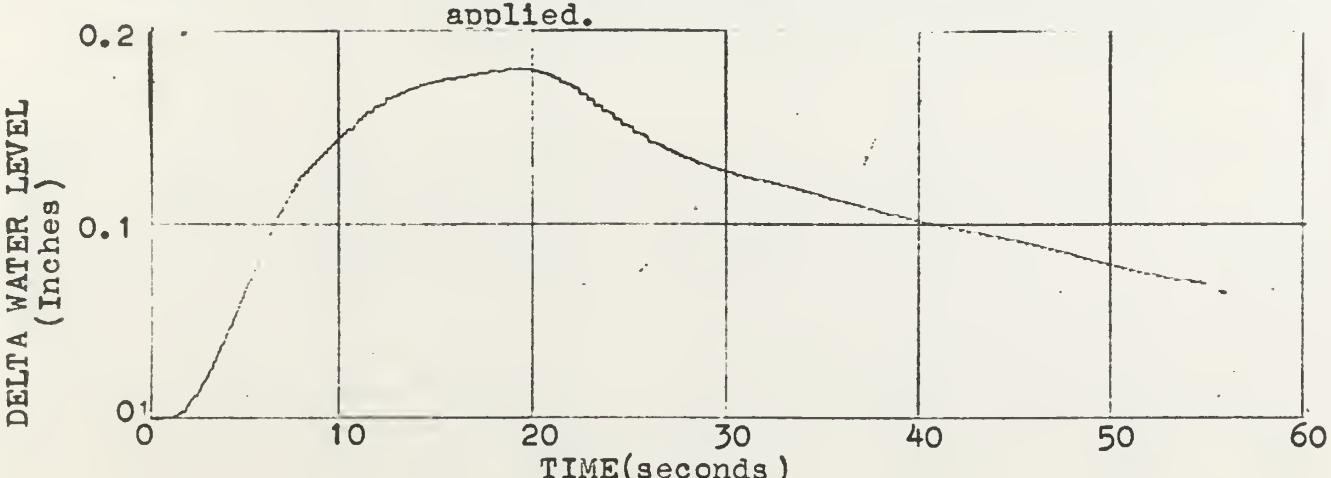


Figure 7-2(b) - DELTA WATER LEVEL VS TIME for delta system at cruising conditions with positive ramp applied.

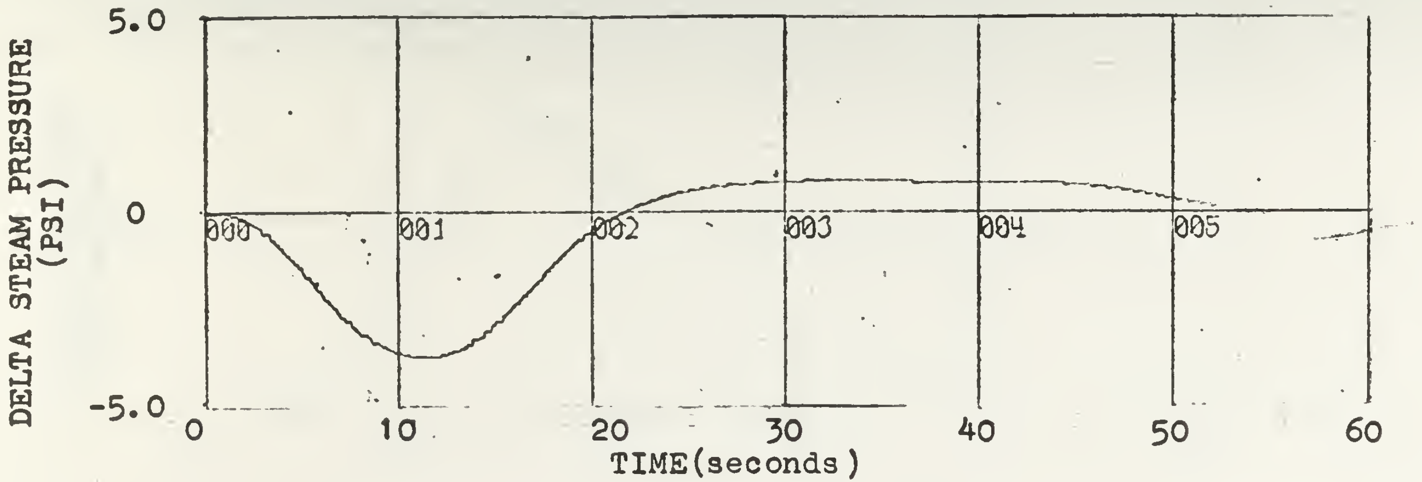


Figure 7-3(a) - DELTA STEAM PRESSURE VS TIME for delta system at cruising conditions with positive ramp applied.

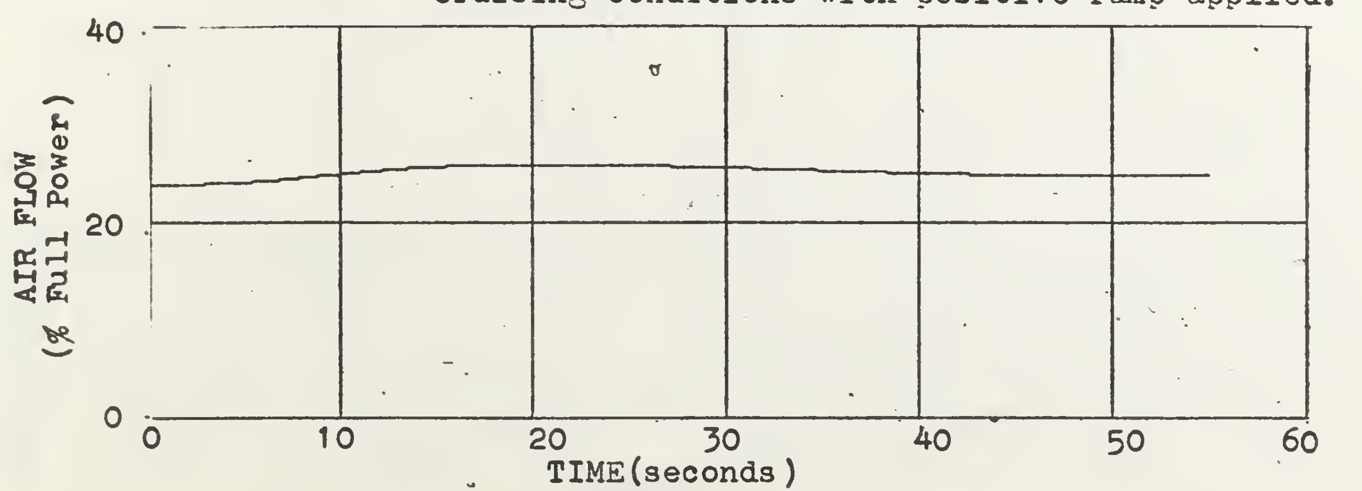


Figure 7-3(b) - AIR FLOW VS TIME for delta system at cruising conditions with positive ramp applied.

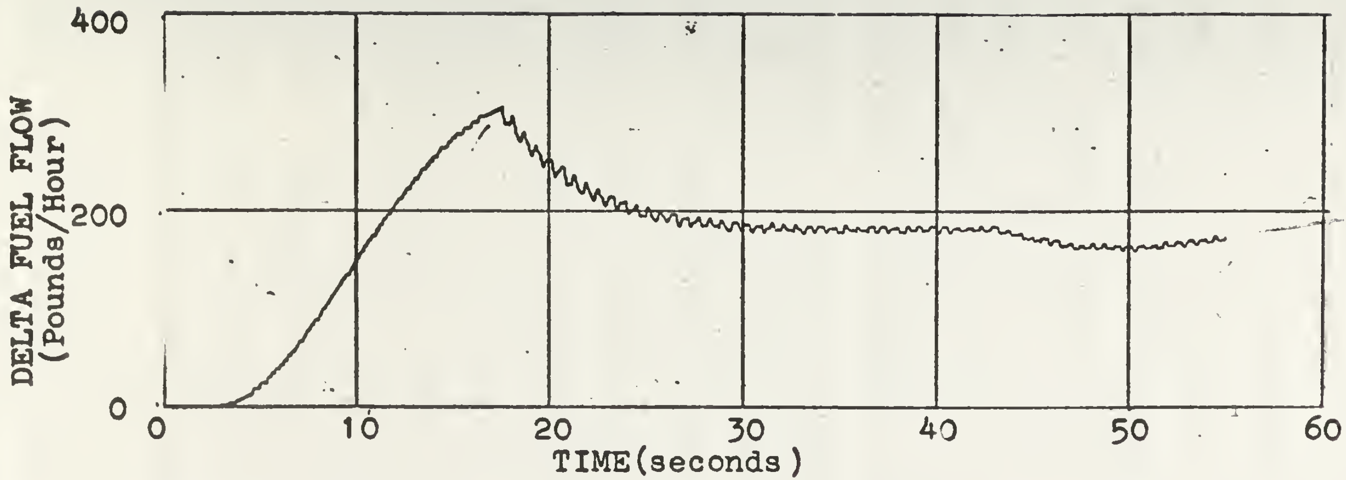


Figure 7-4(a) - DELTA FUEL FLOW for delta system at cruising conditions with positive ramp applied.

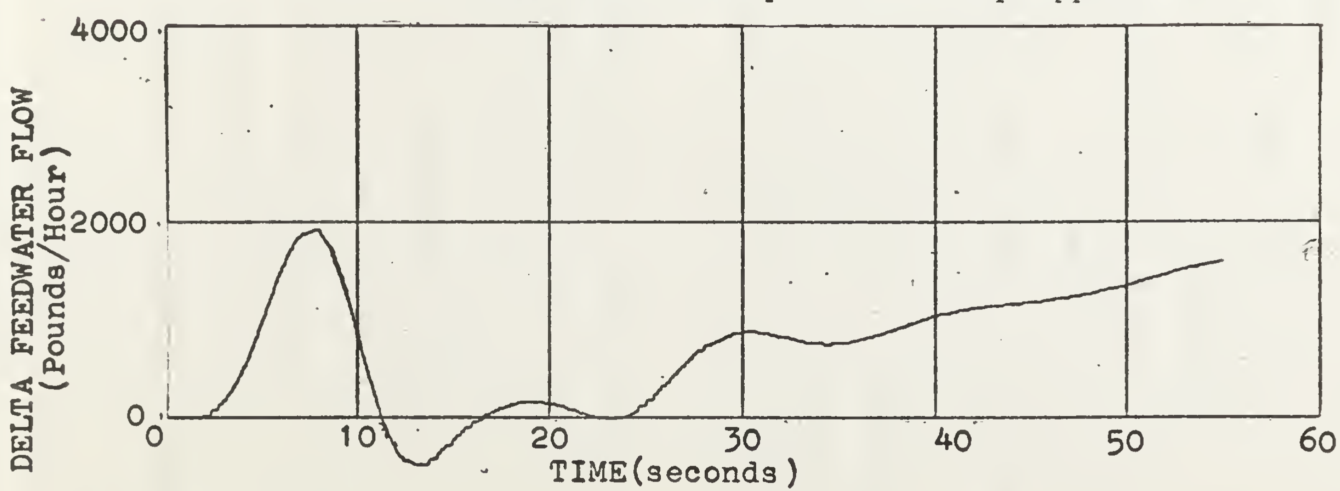


Figure 7-4(b) - DELTA FEEDWATER FLOW VS TIME for delta system at cruising conditions with positive ramp applied.

the steady state value of zero, as shown in figure 7-5(b). The change in boiler steam pressure, given in figure 7-6(a), reaches a minimum of two psig at 36 seconds and then approaches its zero steady state value. Note that there is a small rise in pressure at first as expected; but then at about ten seconds the pressure goes negative due to the response of the feedwater controller, which is somewhat oscillatory (figure 7-7(b)). The air flow, figure 7-6(b) exhibits little change as expected for the small perturbation of the steam flow. The delta fuel flow approaches its final value of -180 lbs/hr with some small oscillations as shown in figure 7-7 (a). The delta feedwater flow, figure 7-7(b), as mentioned above, was oscillatory as in the case of a positive ramp change, and the system is slow, not reaching its final value in the 55 seconds of simulation. These simulations gave reasonable results with the exception of the feedwater. The results, therefore, somewhat proved the validity of the transfer functions given for the delta plant at cruising conditions for perturbations of five per cent around this set point.

7.22 Delta System Simulation at 90 Percent of Full Power Conditions

The complete steam generator with associated control system was simulated at the 90 percent of full power condition using the delta transfer functions as given in figure 7-1. The system was perturbed with a five per cent ramp in both the positive and negative directions as in the previous section. The positive ramp in steam flow from 152,000 lbs/hr to 160,000 lbs/hr in five seconds and held at 160,000 lbs/hr for 50 seconds is shown in figure 7-8(a). The delta drum water level hits a peak of .3 inches in 13 seconds and then approaches the steady state value of zero as shown in figure 7-8(b); the swell observed here is the result of the sudden evaporation in the riser due to the reduced drum pressure caused by the sudden

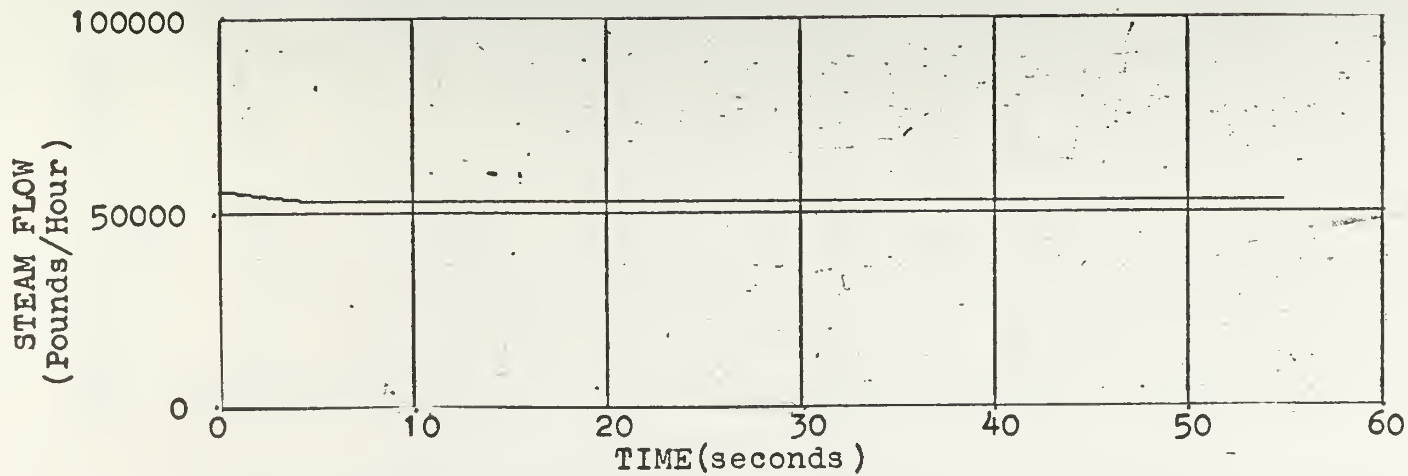


Figure 7-5(a) - STEAM FLOW VS TIME for delta system at cruising conditions with negative ramp applied.

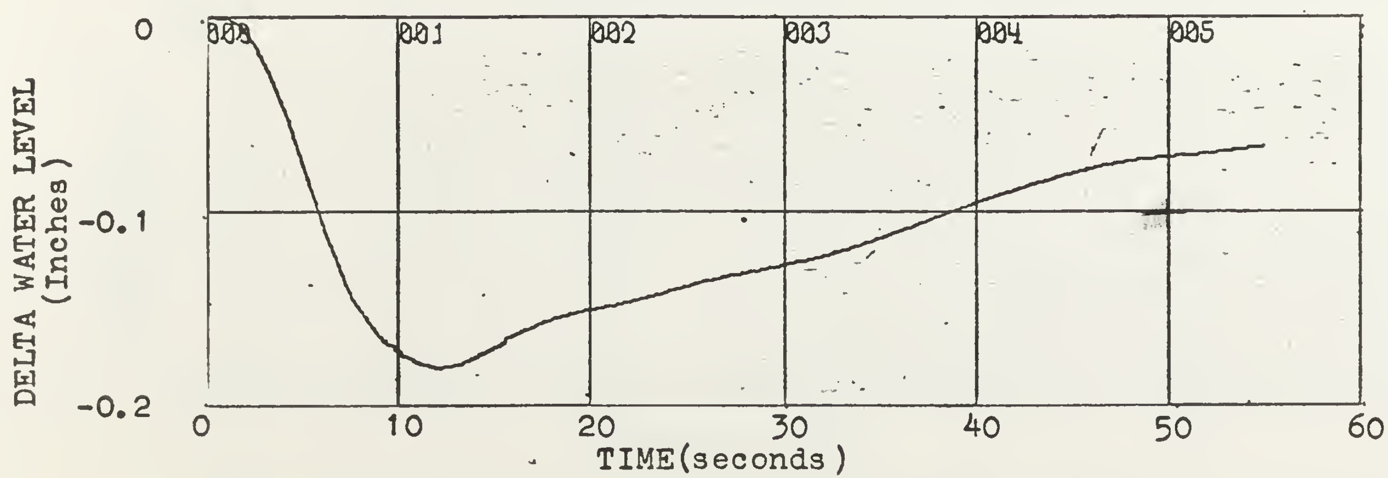


Figure 7-5(b) - DELTA WATER LEVEL VS TIME for delta system at cruising conditions with negative ramp applied.

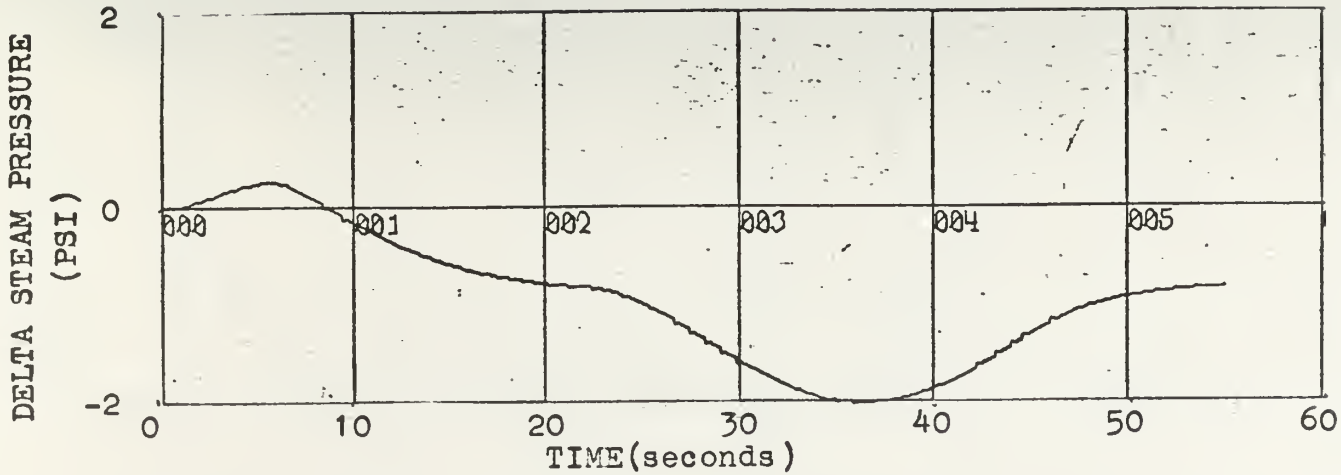


Figure 7-6(a) - DELTA STEAM PRESSURE VS TIME for delta system at cruising conditions with negative ramp applied.

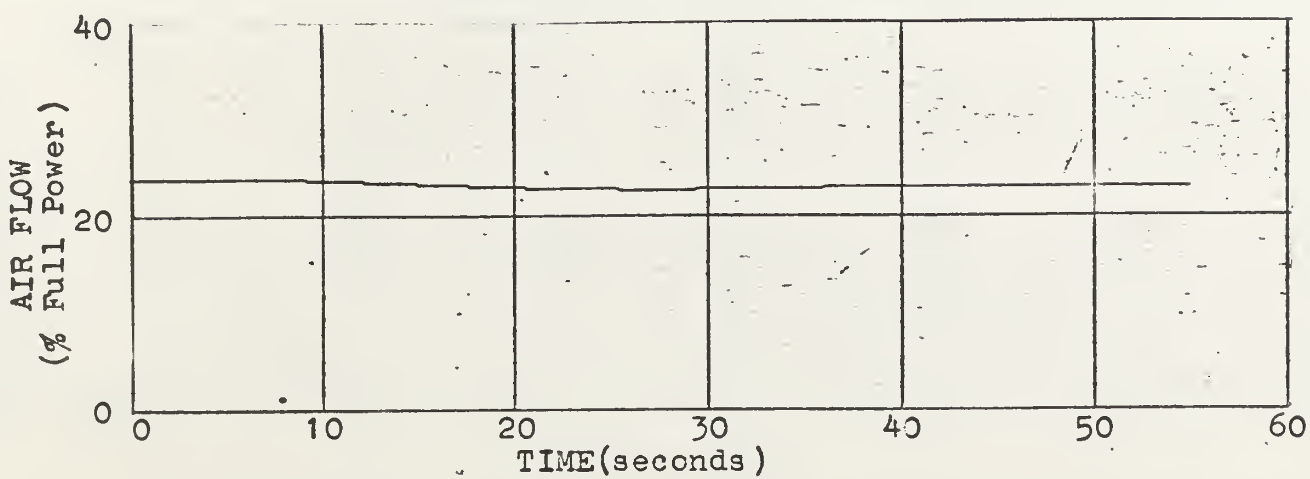


Figure 7-6(b) - AIR FLOW VS TIME for delta system at cruising condition with negative ramp applied.

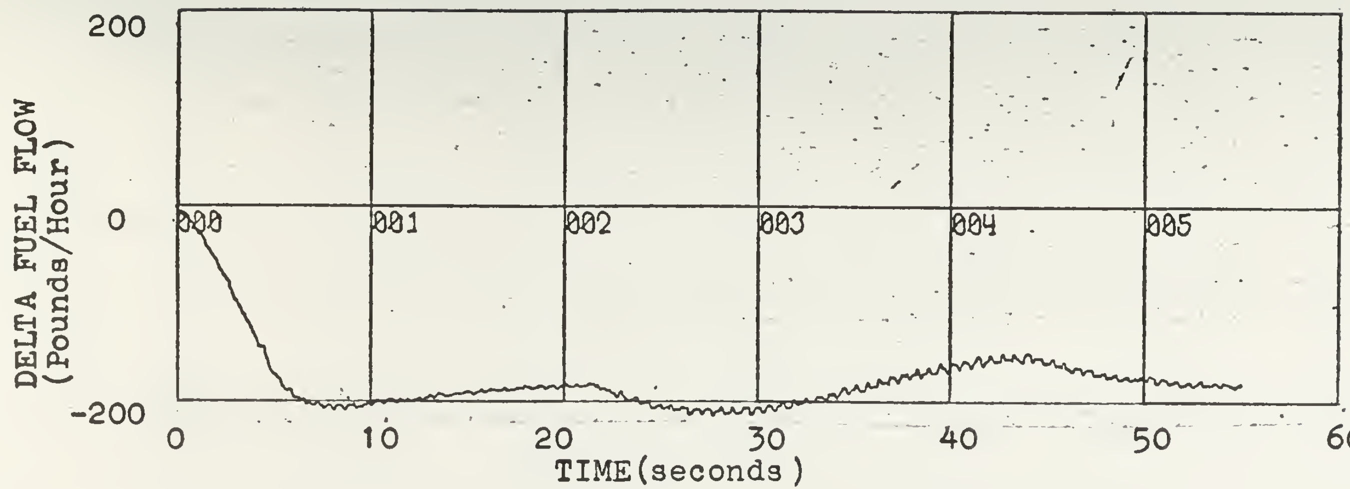


Figure 7-7(a) - DELTA FUEL FLOW VS TIME for delta system at cruising conditions with negative ramp applied.

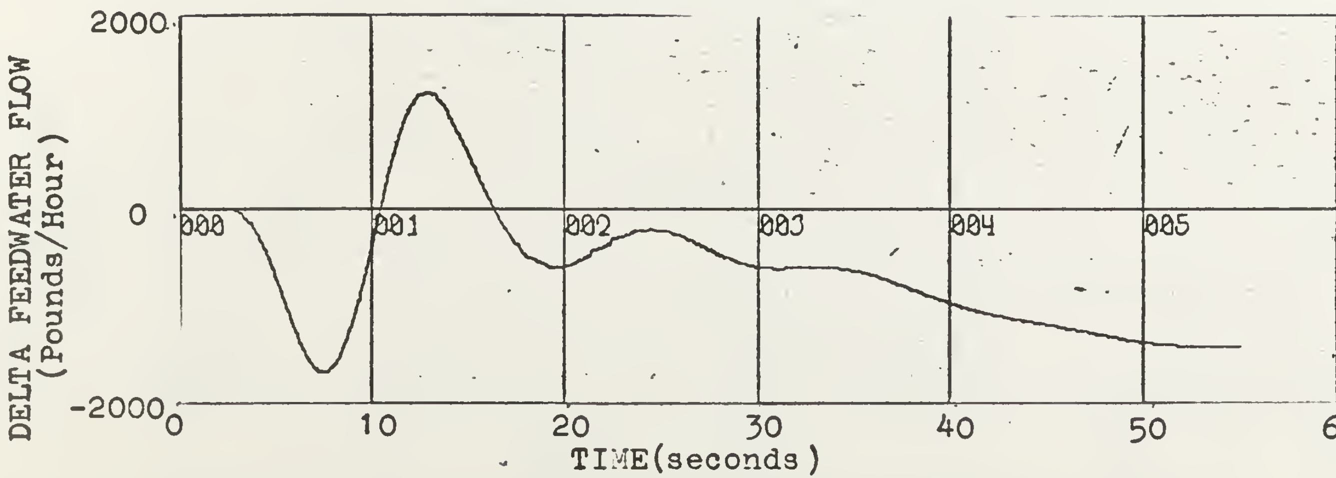


Figure 7-7(b) - DELTA FEEDWATER FLOW VS TIME for delta system at cruising conditions with negative ramp applied.

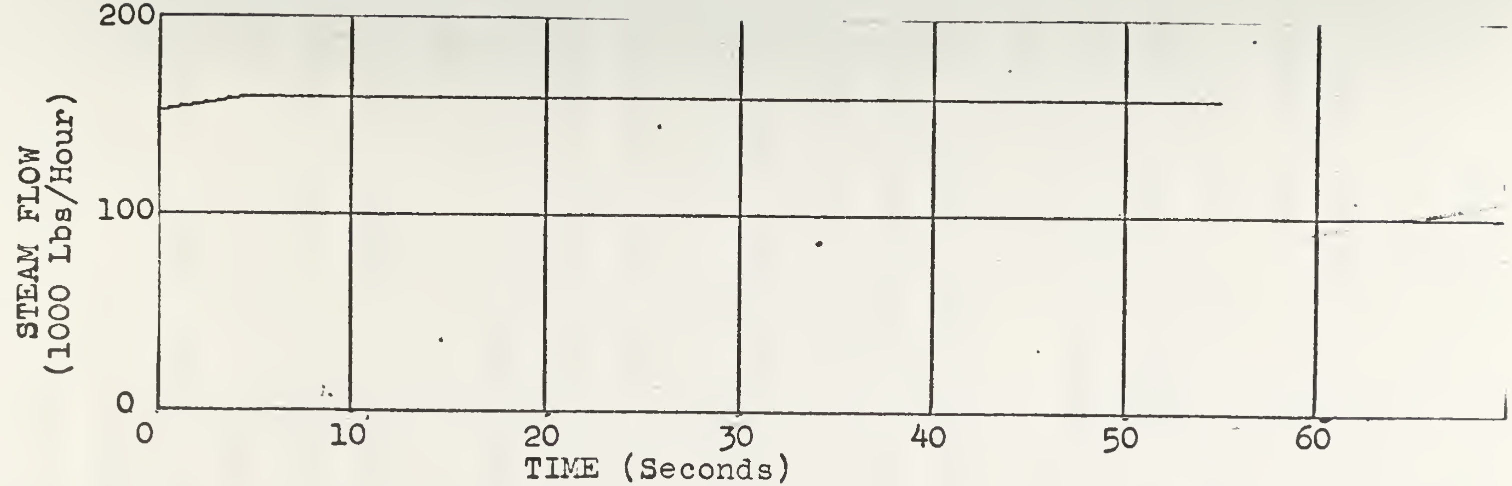


Figure 7-8 (a) - STEAM FLOW VS TIME for delta system at 90 percent condition with a positive ramp applied

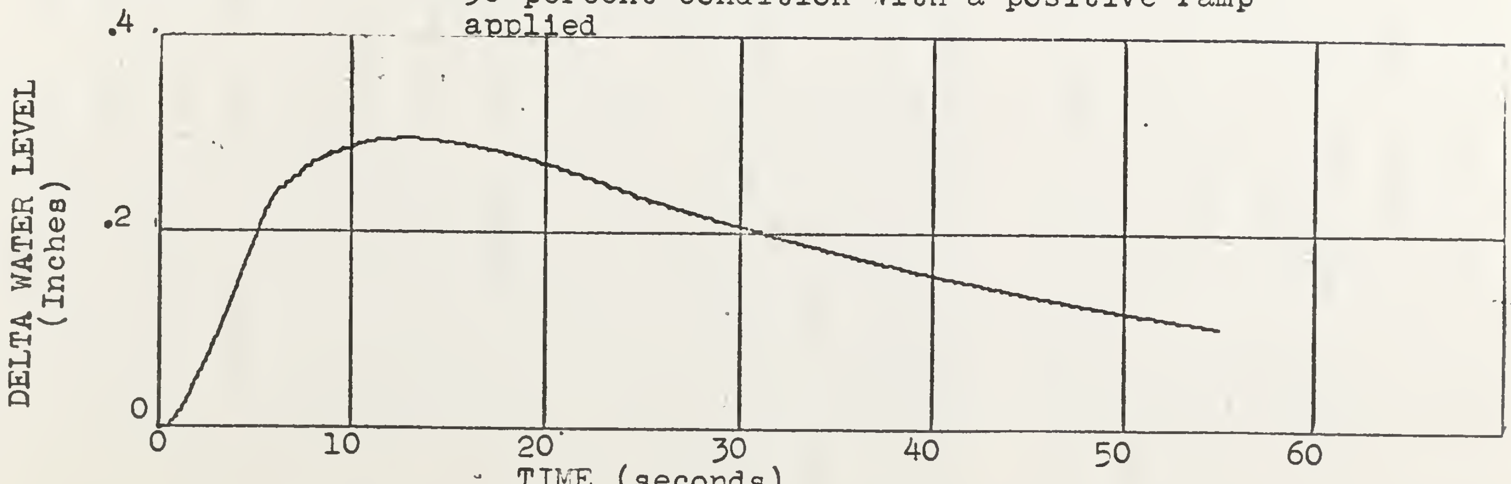


Figure 7-8 (b) - DELTA WATER LEVEL VS TIME for a delta system at 90 percent condition with a positive ramp applied

increases in steam flow. This phenomenon is also observed in the delta system at cruising conditions when the positive ramp change in steam flow is applied. Figure 7-9(b) shows that the air reaches its final value of 84 per cent quality in 20 seconds and remains at that value. The change in fuel flow, figure 7-10(a), has a slight overshoot and arrives at its final value of 640 lbs/hr in 25 seconds. The delta feedwater flow shown in figure 7-10(b) still exhibits the oscillatory nature due to the feedwater level control system as explained by the root locus study in section 6.92, and the change in feedwater is approaching its final value of 8000 lbs/hr and would probably steady out at this value about two minutes after the change in load.

A negative ramp in steam flow was applied to the delta system at 90 per cent condition which lowered the steam flow from 152,000 lbs/hr to 144,000 lbs/hr in five seconds; this steam flow is shown in figure 7-11(a). The change in water level to this negative ramp is given in figure 7-11(b); the drum water level reaches a minimum of -.38 inches in ten seconds, then approaches a zero steady state value. The response of the delta steam pressure was oscillatory and negative, as shown in figure 7-12(a); this is due in part to the oscillatory nature of the feedwater control system as explained in section 6.92. The steam pressure should have had a small positive overshoot in the first ten seconds and then crossed the zero axis and had a negative delta pressure as it approached its zero final value. The air flow, given in figure 7-12(b), exhibits the expected response settling out at a final value of about 75% in 30 seconds. The change in fuel flow is given in figure 7-13(a), which shows that the delta fuel flow settles out at -750 lbs/hr in about 35 seconds. The response of the delta feedwater flow was again oscillatory as it had been in all other runs; this

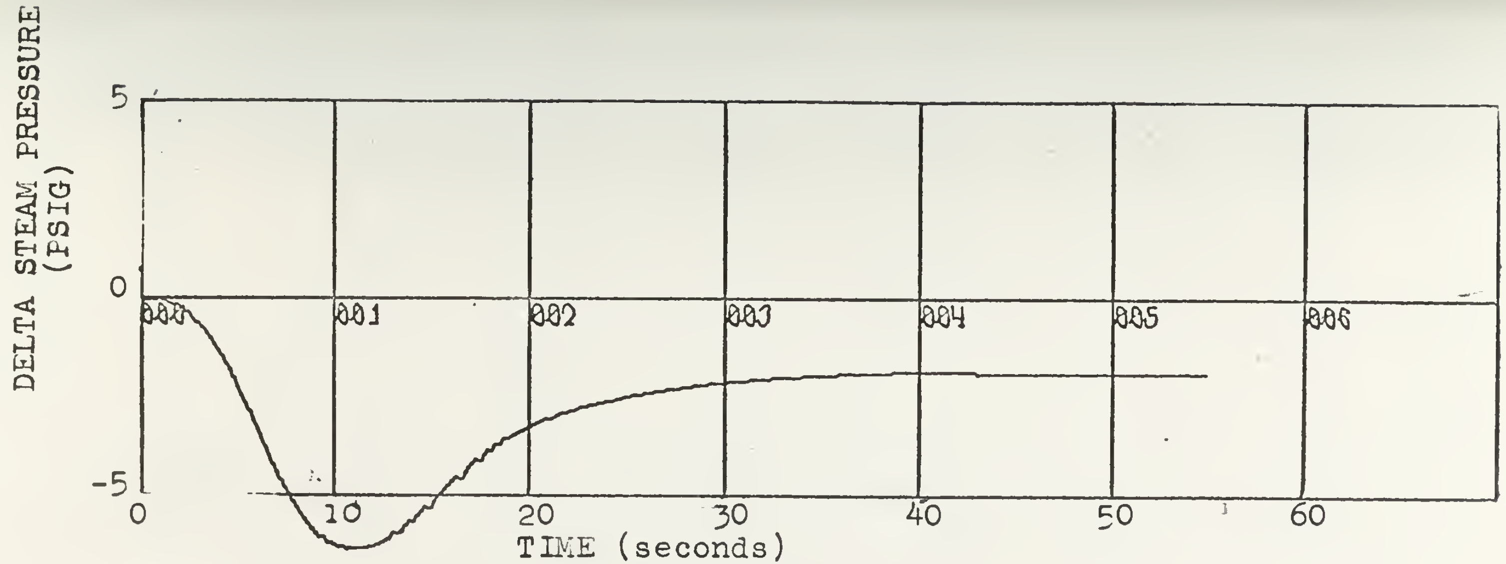


Figure 7-9(a) - DELTA STEAM PRESSURE VS TIME for a delta system at 90 percent condition with a positive ramp applied

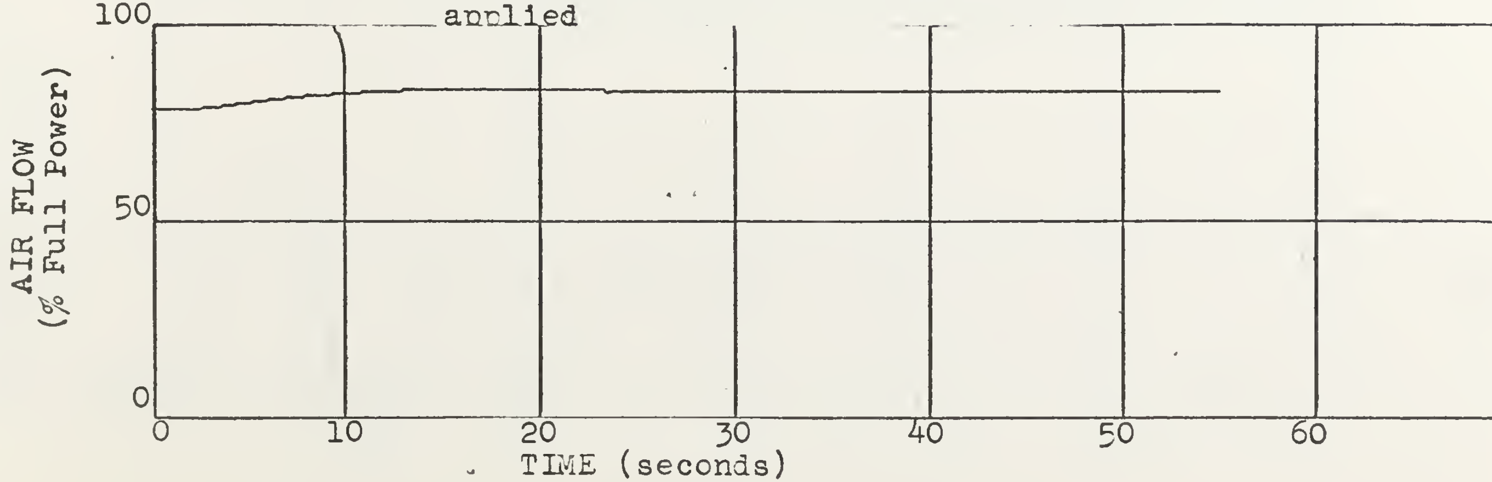


Figure 7-9(b) - AIR FLOW VS TIME for a delta system at 90 percent condition with a positve ramp applied

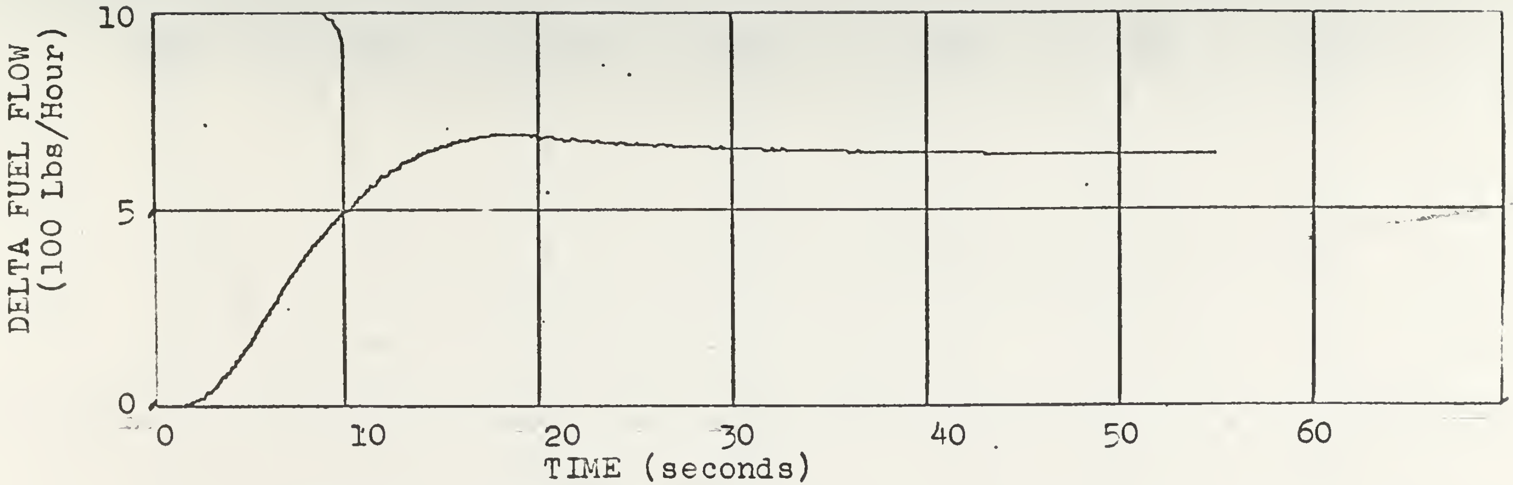


Figure 7-10(a) - DELTA FUEL FLOW VS TIME for delta system at 90 percent condition with a positive ramp applied

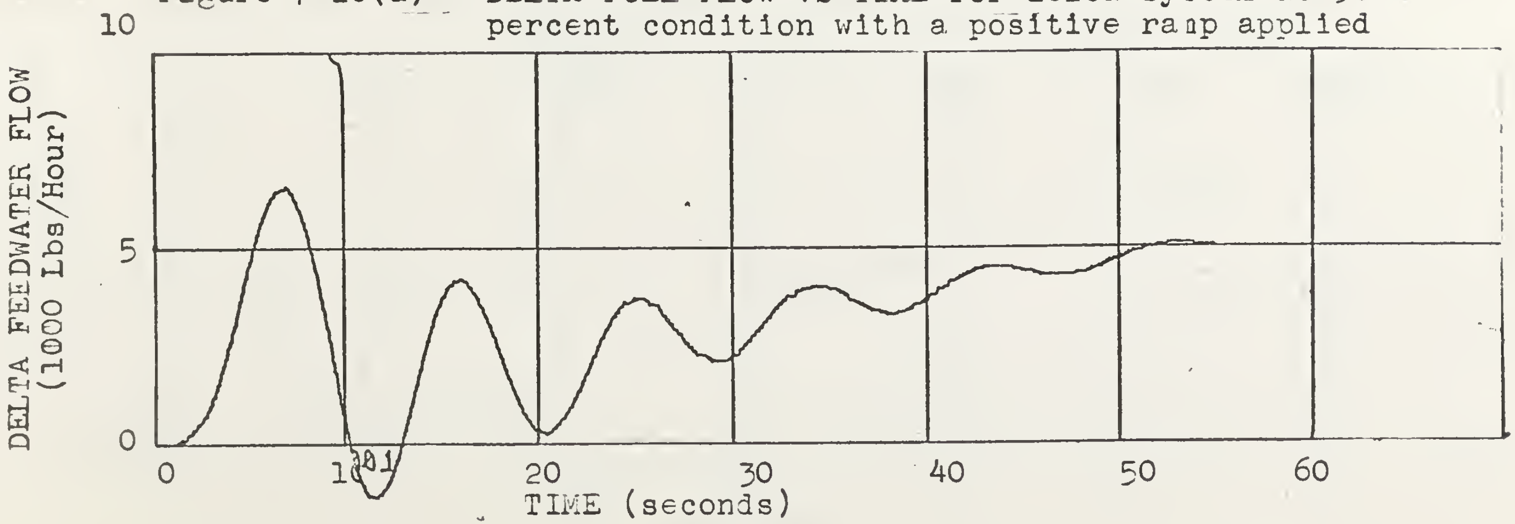


Figure 7-10(b) - DELTA FEEDWATER FLOW VS TIME for delta system at 90 percent condition with a positive ramp applied

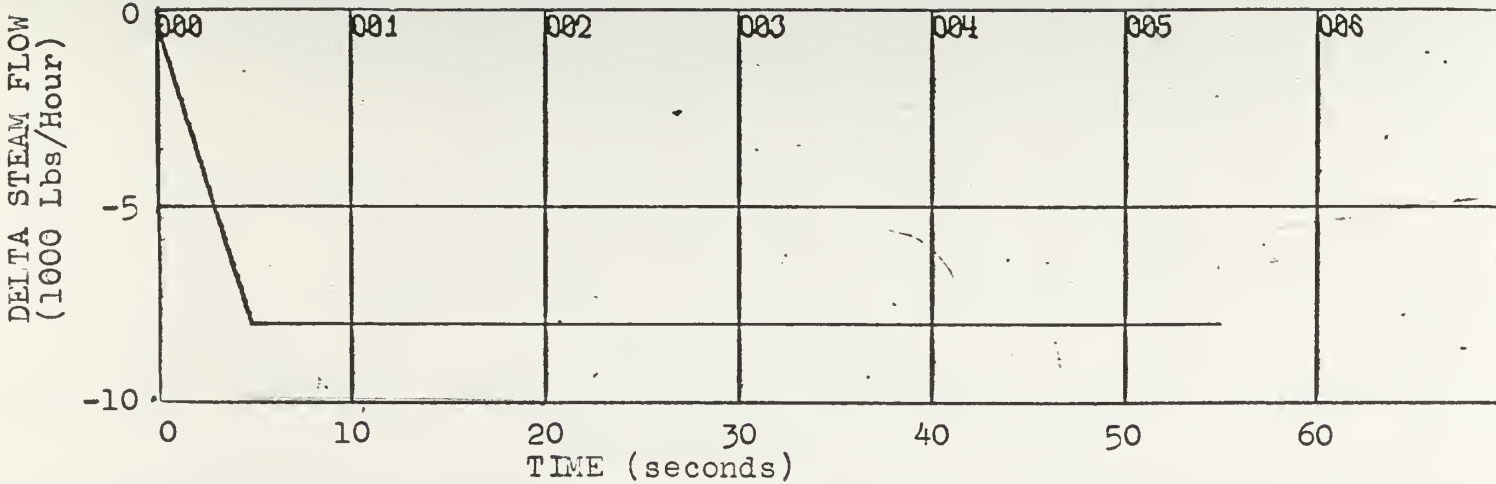


Figure 7-11 (a) - DELTA STEAM FLOW VS TIME for delta system at 90 percent condition with a negative ramp applied

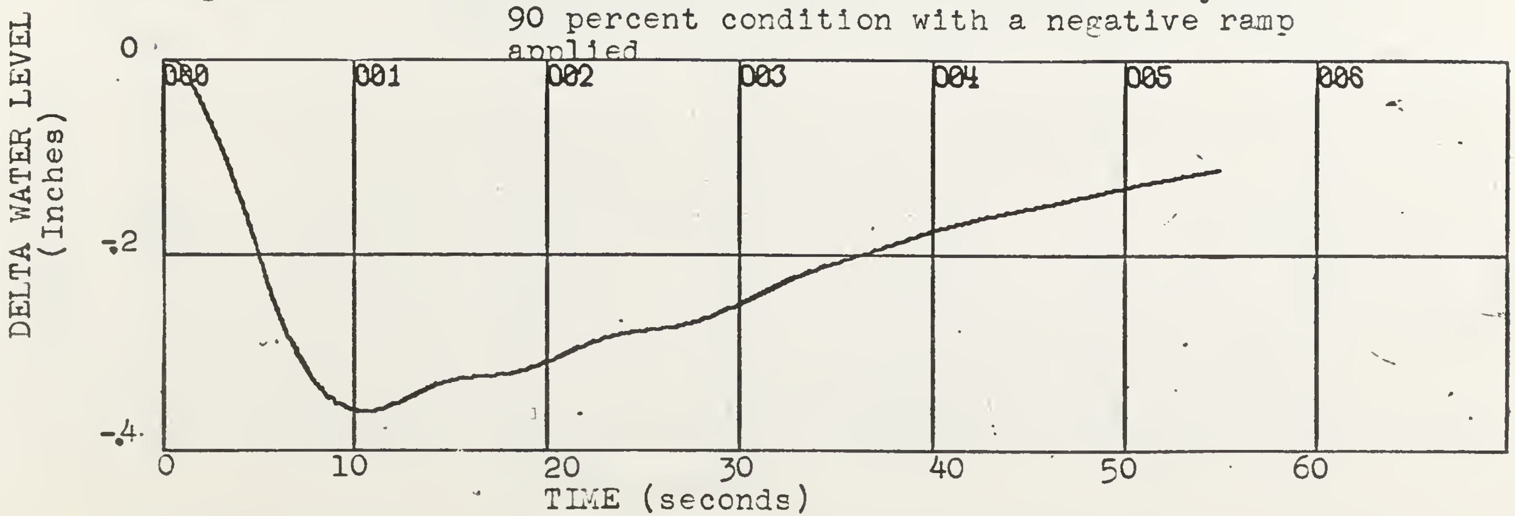


Figure 7-11 (b) - DELTA WATER LEVEL VS TIME for delta system at 90 percent condition with a negative ramp applied

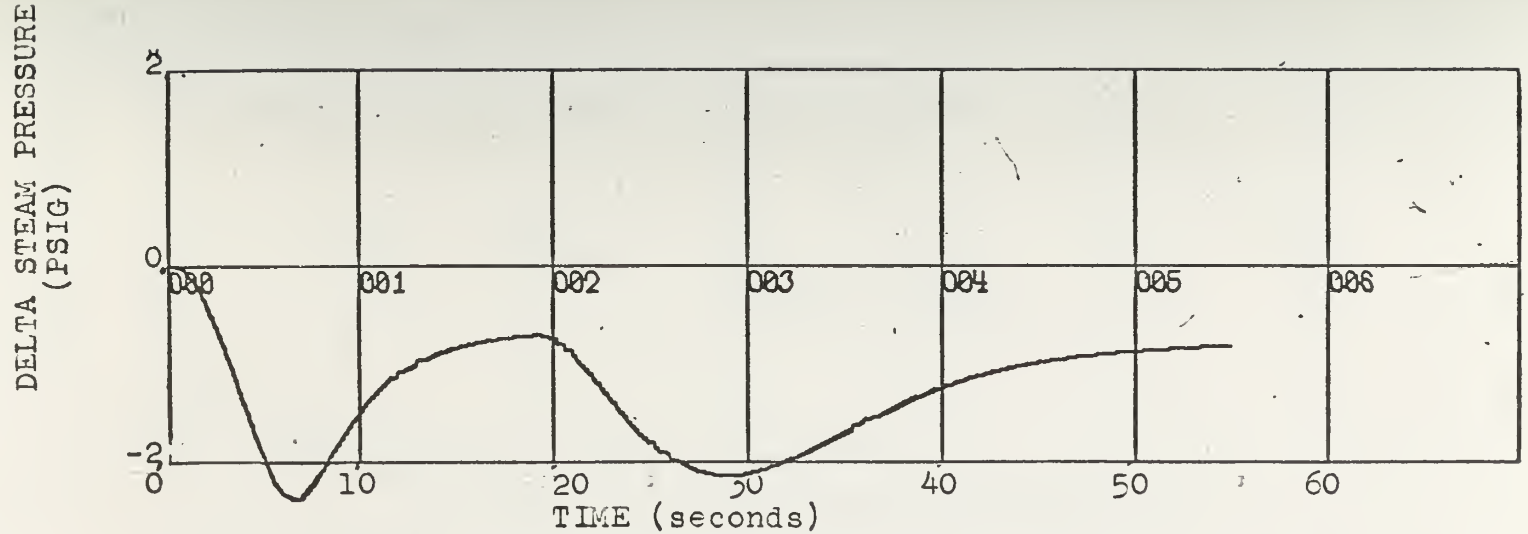


FIGURE 7-12(a) - DELTA STEAM PRESSURE VS TIME for delta system at 90 percent condition with a negative ramp applied

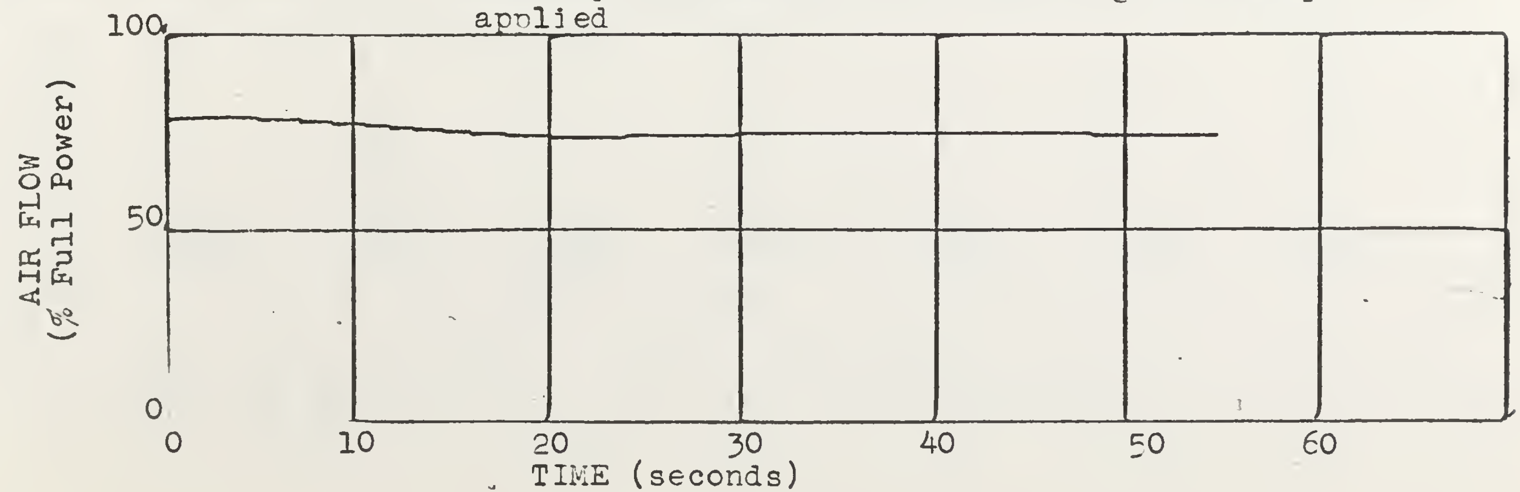


FIGURE 7-12(b) - AIR FLOW VS TIME for delta system at 90 percent condition with a negative ramp applied

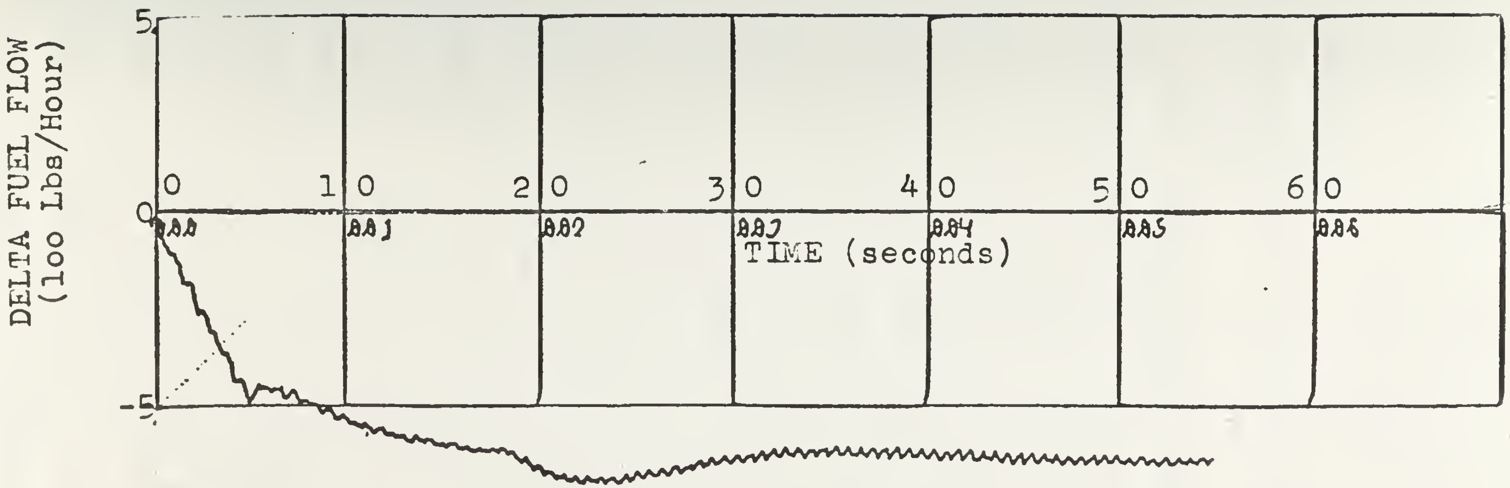


Figure 7-13(a) - DELTA FUEL FLOW VS TIME for delta system at 90 percent condition with a negative ramp applied

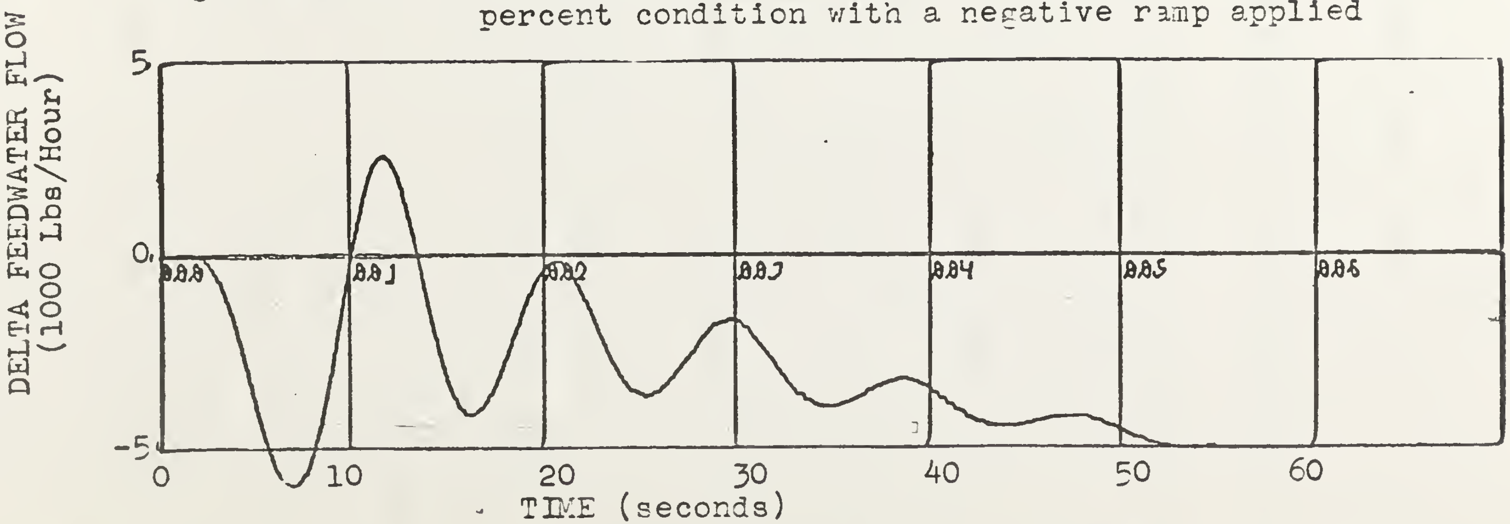
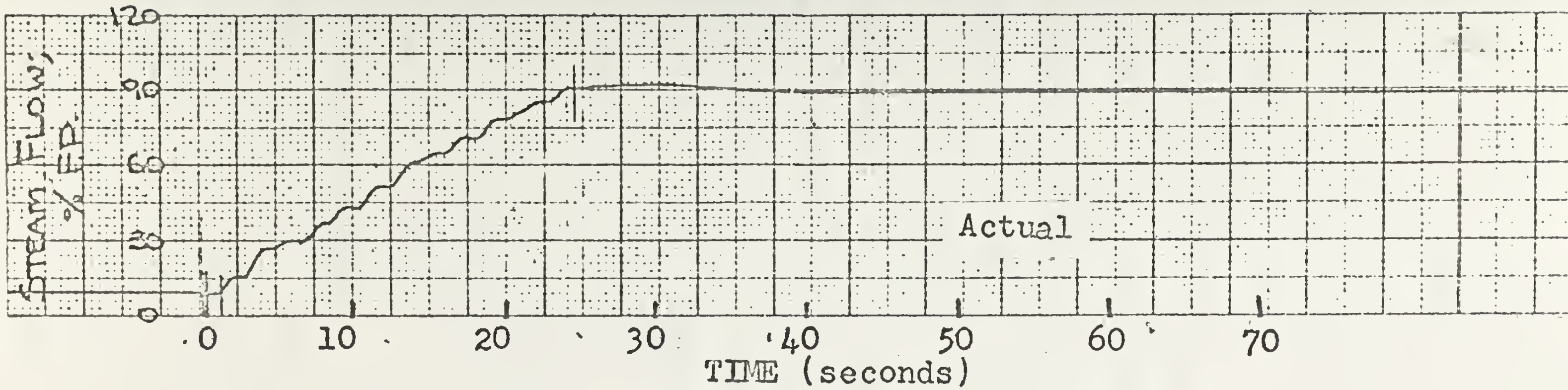


Figure 7-13(b) - DELTA FEEDWATER FLOW VS TIME for delta system at 90 percent condition with a negtive ramp applied

simulation was for a period of 55 seconds; therefore, the delta feedwater flow was approaching, but did not reach its final value of -8000 lbs/hr in this time as shown in figure 7-13(b). The delta system at 90 per cent conditions with the negative ramp exhibited the expected transient responses with the exception of the delta steam pressure response as explained above.

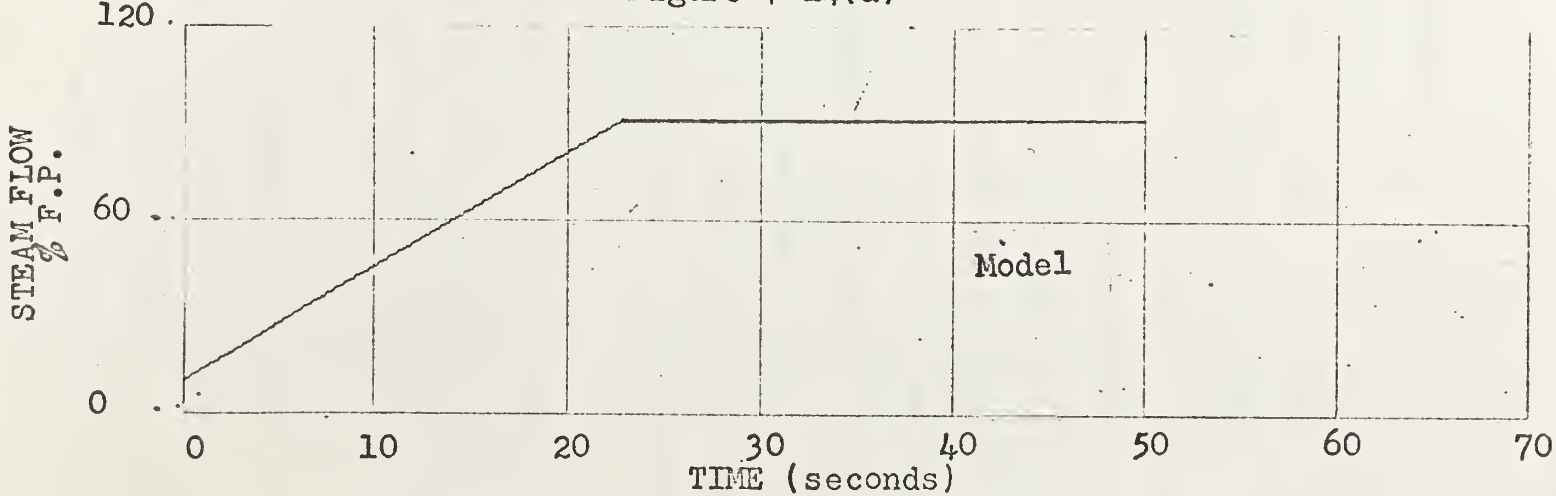
7.3 Simulation of the DLG-9 Steam Generator with the Non-Linear Air Flow System

The steam generator system was simulated, with the non-linear air flow control system shown in figure 4-3, as explained in section 4.91, replacing the linear system at two operating points as in the delta system simulation of the previous section. The steam flow was ramped from ten to 90 per cent of full power in 23 seconds as shown in figure 7-14(b), which is the same as the steam flow ramp used by NBTL [4] in conducting their test runs on actual boilers shown in figure 7-14(a), and the responses from these test runs conducted by NBTL were used as the reference for comparison with the digital computer simulation results. The digital computer simulations were run using three different transfer functions for the boiler, namely the linear delta transfer function for the crusing conditions, the linear delta transfer function for the 90 per cent full power conditions, and lastly non-linear delta transfer functions for the boiler which are a function of the steam flow. These last transfer functions for the boiler are generated by using the cruising conditions transfer functions for values of steam flow below cruising conditions; and for values between cruising conditions and 90 per cent full power the gains and time constants of the boiler transfer functions are given a value as a function of steam flow using a straight line approximation between the values at cruising conditions and 90 per cent full power.



Steam Flow vs Time for maneuvering a DLG-9 boiler from ten to 90 per cent full power in 23 seconds

Figure 7-14(a)

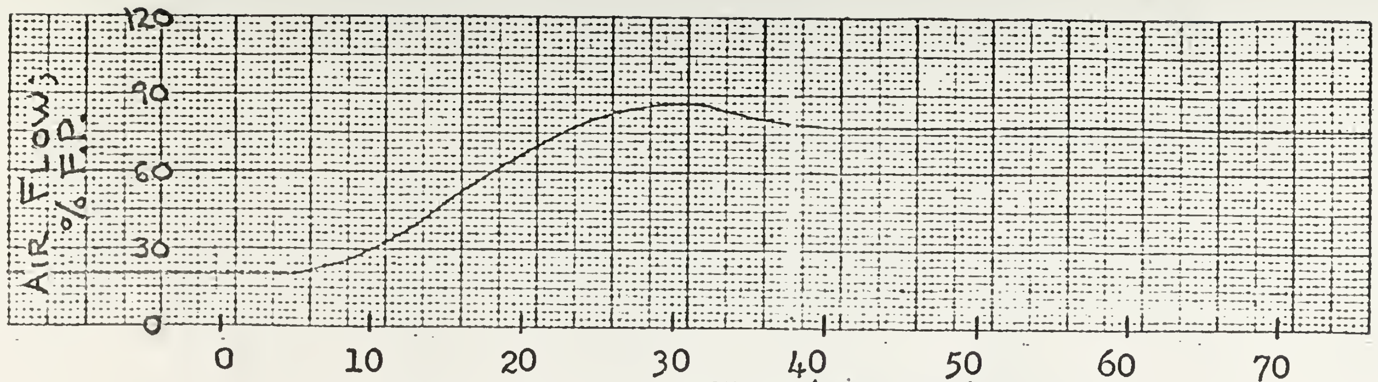


Steam flow vs Time for maneuvering a DLG-9 boiler from ten to 90 per cent full power in 23 seconds

Figure 7-14(b)

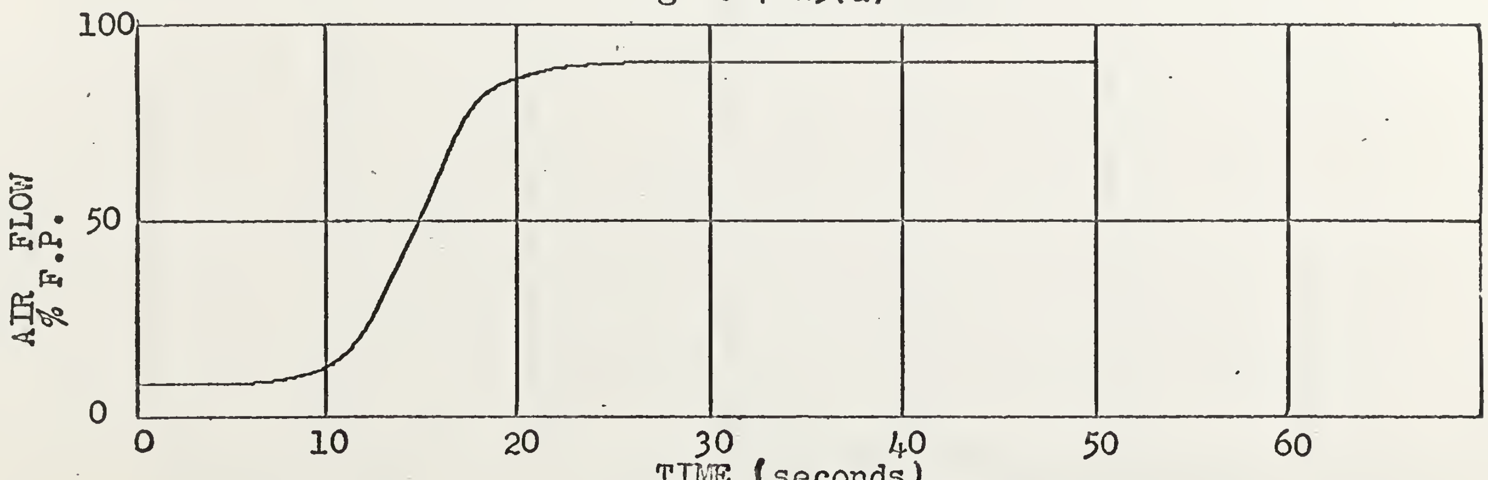
The air flow comparisons are shown in figures 7-15(a) through 7-15 (d), where figure 7-15(a) is the air flow test data from a run on the DLG-9 test boiler at NBTL [4]. The air flow figure 7-15(b), obtained using the cruising conditions transfer functions for the boiler, hits a peak of 80% at 25 seconds as compared with 87% in 30 seconds from the test data; also the air flow from the test data settles out at 78% of full power at about 45 seconds, whereas the air flow of figure 7-15(b) has a value of 70% at 50 seconds. The air flow obtained using the 90% transfer functions for the boiler, shown in figure 7-15(c), has no overshoot but rather it reaches its final value of 90% of full power at about 30 seconds. This final value is higher than the test data results of 78%. The air flow obtained by using boiler transfer functions which are a function of the steam flow is given in figure 7-15(d). The response has no overshoot and settles out at about 90% of full power in 28 seconds. This result is of the same shape as the air flow using the 90% of full power boiler transfer functions. It should be noted in the figures that the air for the test boiler has an initial value of about 20%, whereas the air for the simulations on the digital computer has an initial value of 10%.

The fuel oil comparisons are shown in figures 7-16(a) through 7-16(d). The fuel oil flow from NBTL test boiler for the 10-90% of full power run is shown in figure 7-16(a). It hits a peak of 108% at 30 seconds and settles out to 88% of full power in 70 seconds. Using the cruising conditions transfer functions for the boiler in the simulated run, the fuel oil hits a peak of 88% full power at 25 seconds and settles out to a final value of 70 per cent in 70 seconds. Using the 90% boiler transfer functions the fuel oil flow hits a peak of 102% at 39 seconds and has a value of 90% of full power at 50 seconds. This response is shown in figure 7-16(c).



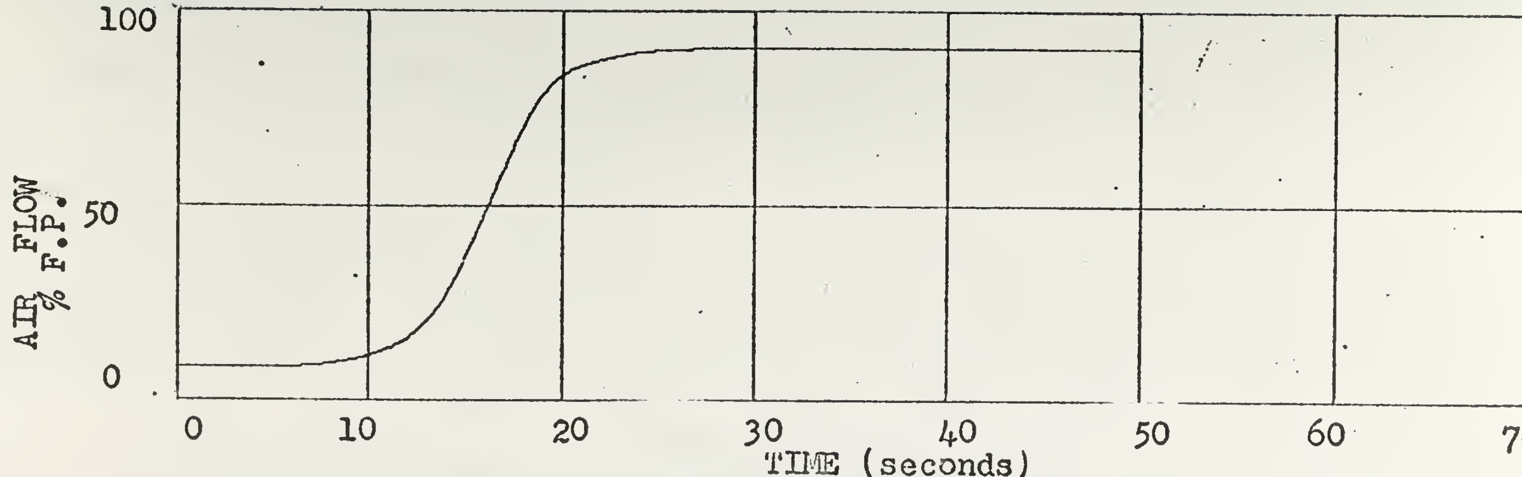
Air Flow vs Time for the actual DLG-9 Boiler

Figure 7-15(a)



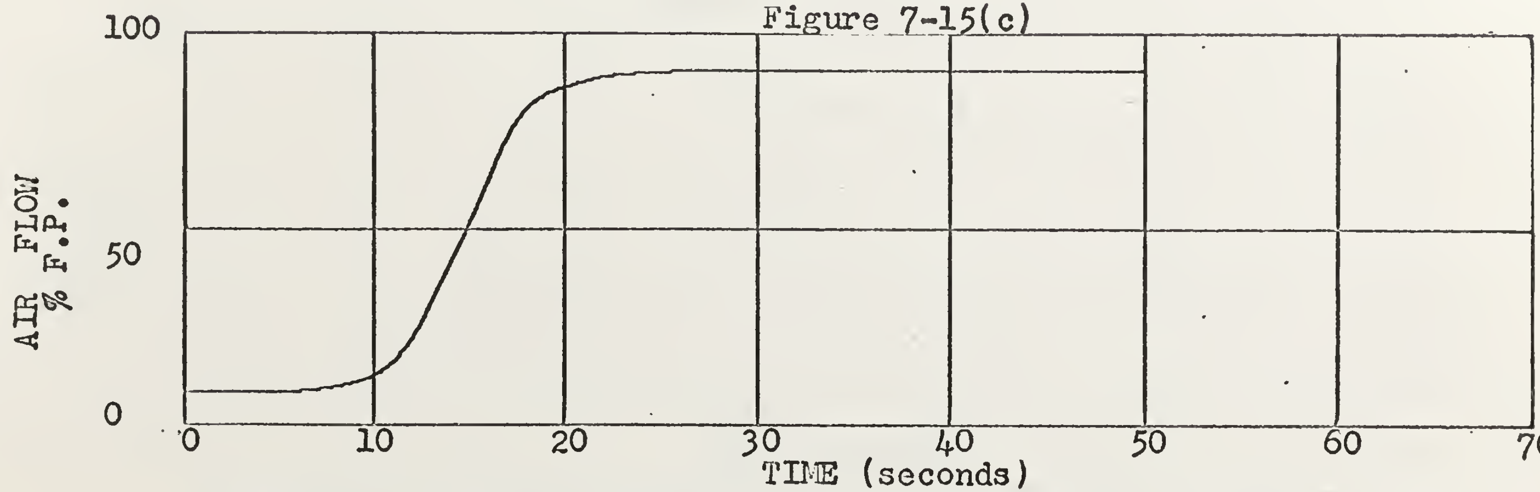
Air Flow vs Time for the DLG-9 Model Boiler with Cruising Conditions Transfer Functions

Figure 7-15(b)



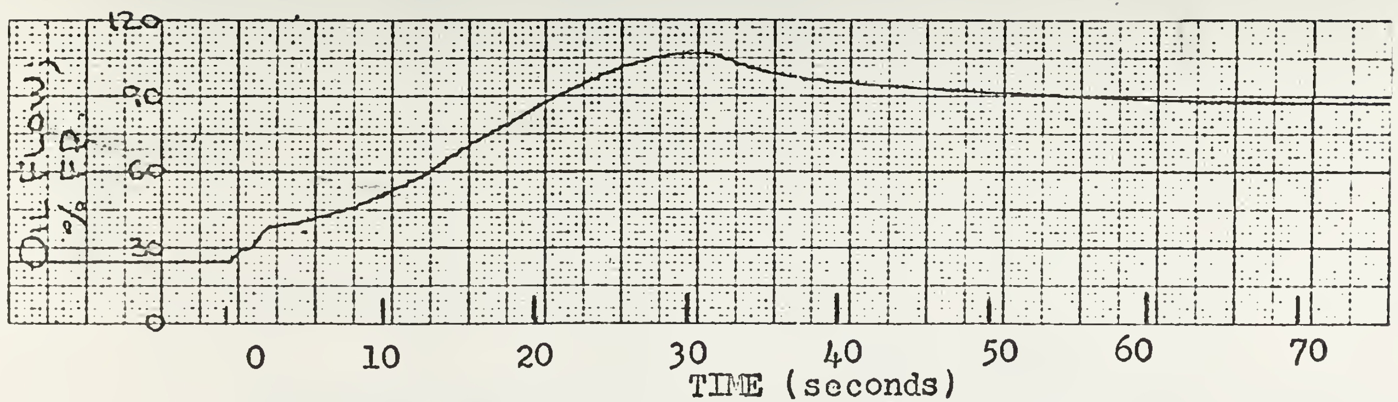
Airflow vs Time for the DLG-9 Model Boiler with 90 per cent Transfer Functions

Figure 7-15(c)



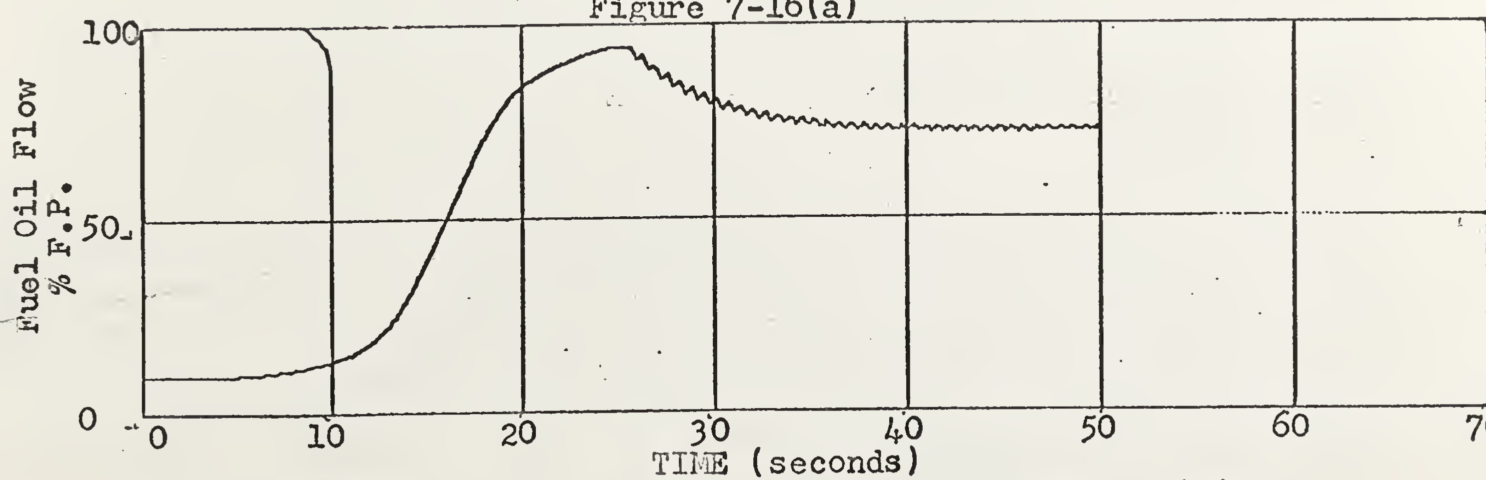
Airflow vs Time for the DLG-9 Model Boiler with non linear Transfer Functions

Figure 7-15(d)



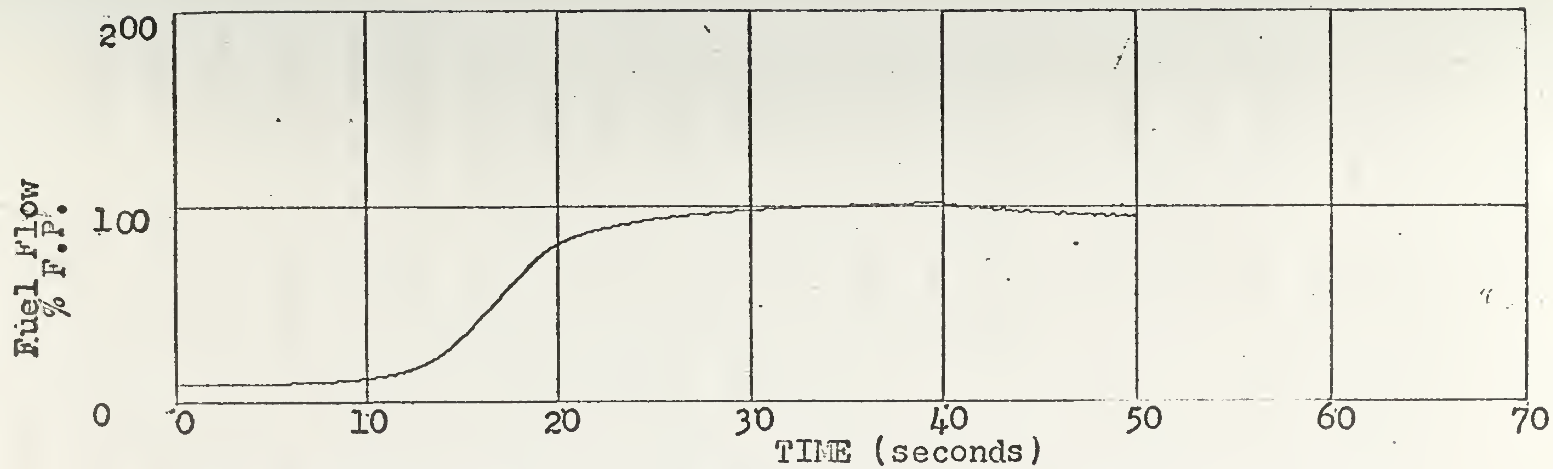
Fuel Flow vs Time for the actual DLG-9 Boiler

Figure 7-16(a)



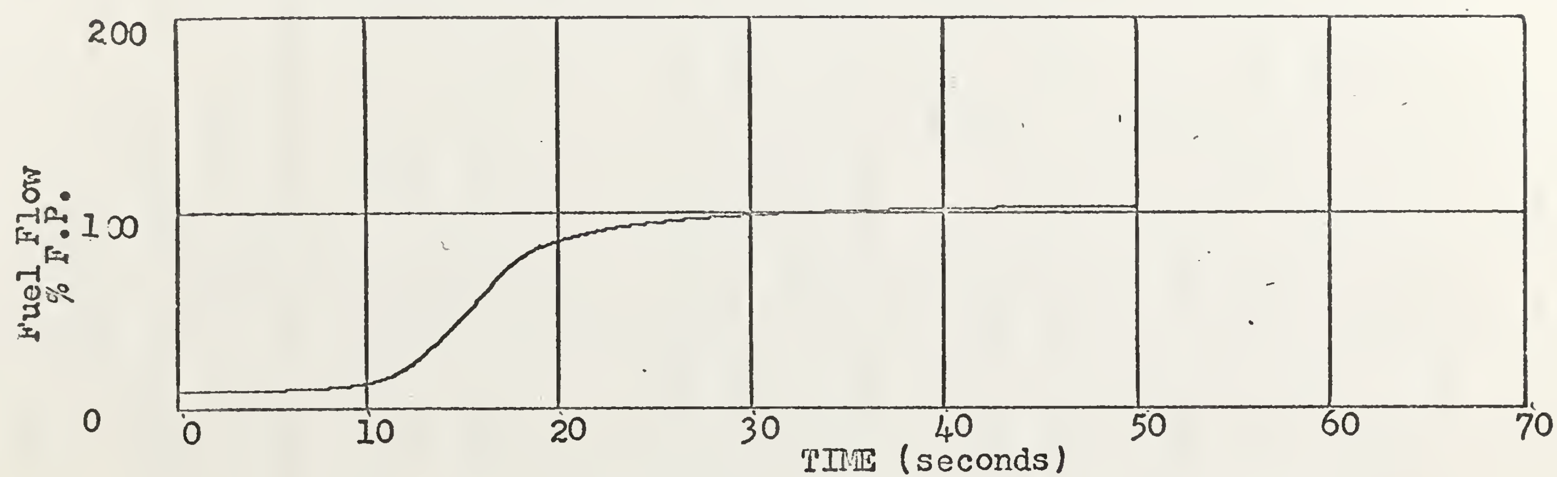
Fuel Flow vs Time for the DLG-9 Model Boiler with Cruising Conditions Transfer Functions

Figure 7-16(b)



Fuel Flow vs Time for the DLG-9 Model Boiler with 90 per cent Transfer Functions

Figure 7-16(c)



Fuel Flow vs Time for the DLG-9 Model Boiler with non linear Transfer Functions

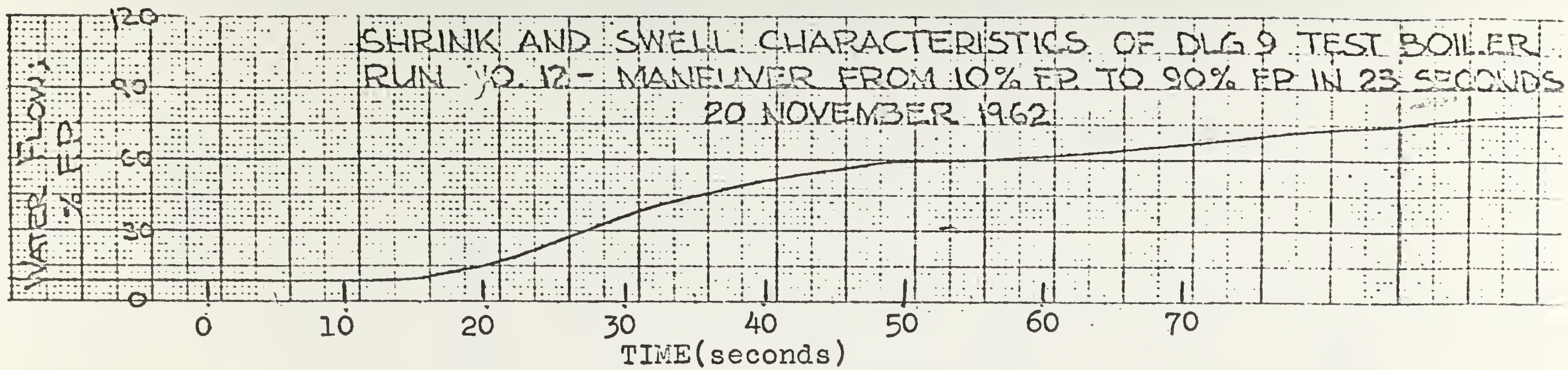
Figure 7-16(d)

The response of the fuel oil flow using the boiler transfer functions as a function of steam flow is shown in figure 7-16(d). This response has no overshoot and settles out to a value of 102% after 40 seconds.

The water flow responses are shown in figures 7-17(a) through 7-17(d). The test run response of the actual boiler is shown in figure 7-17(a). This response shows that the system is extremely slow with no oscillations. The responses from the simulated boiler show that there is one or several transfer functions for this system in error or that the method of simulation is in error. In all three cases the water response neglecting the oscillations is somewhat close to the actual. Using the cruising conditions boiler transfer function, the water response, shown in figure 7-17(b), has a value of 36% at 50 seconds, whereas the actual response of the boiler, figure 7-17 (a), has a value of 60%. With the 90% conditions after 50 seconds the water flow has a value of 56% as shown in figure 7-16(c); and with the boiler transfer functions as a function of steam flow, the water response, figure 7-17 (d), has a value of 50% at 50 seconds.

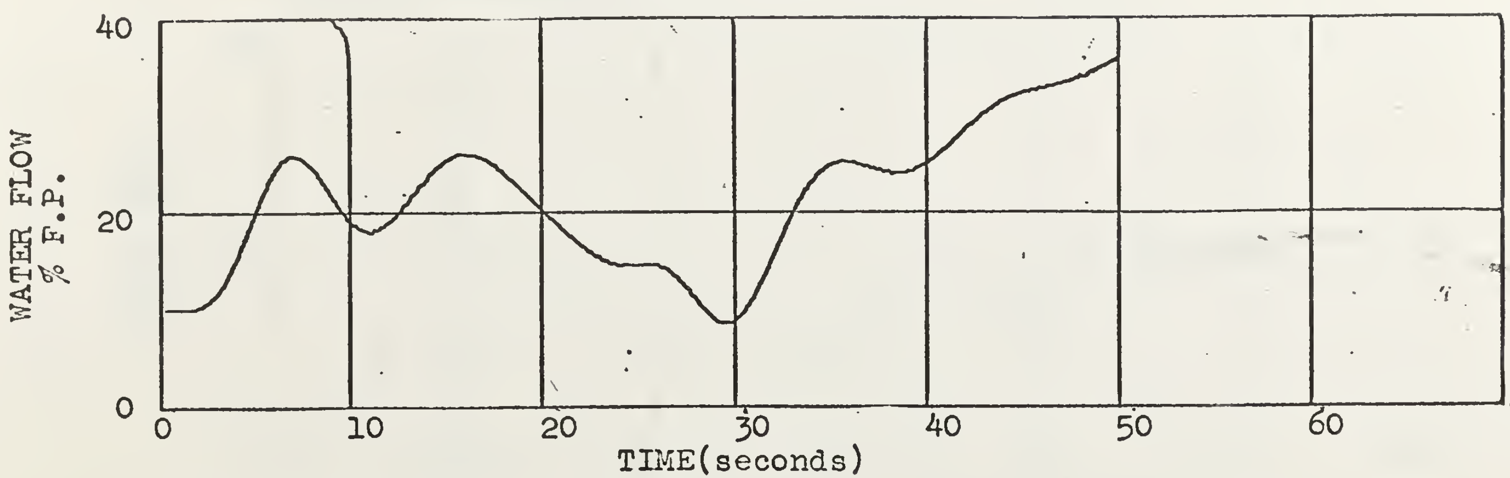
The superheater outlet pressure for the actual boiler is shown in figure 7-18(a), and the outlet pressure for the simulated boiler using the transfer functions as a function of steam flow, is shown in figure 7-18(b). The actual boiler has a minimum pressure of 1115 psig, whereas the simulated boiler has a minimum of 349 psig. Using the cruising conditions transfer functions, the minimum pressure is 1076 psig; and using the 90% full power transfer functions the minimum pressure is 1081 psig. These minimums for the actual and the simulated boiler all occur at 23 seconds.

The water level of the actual boiler, shown in figure 7-19(a), has a peak of 6.0 inches. For the simulated boiler using the cruising conditions transfer functions, the peak water level was 7.7 inches; and for the 90%



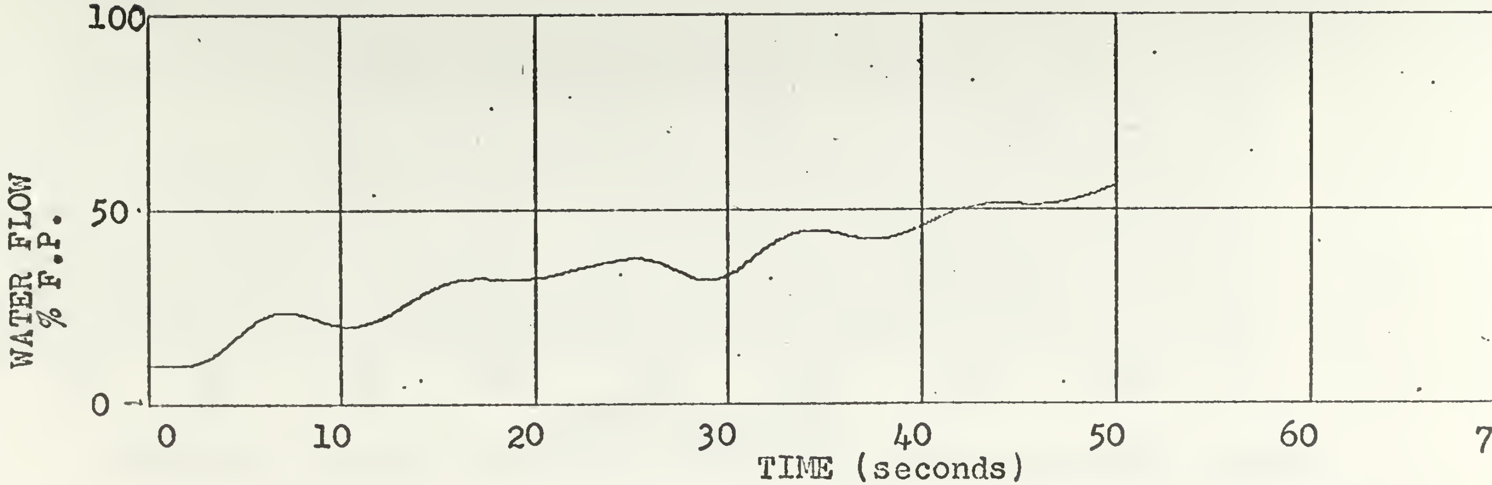
WATER FLOW vs TIME for the actual DLG-9 Boiler

Figure 7-17(a)



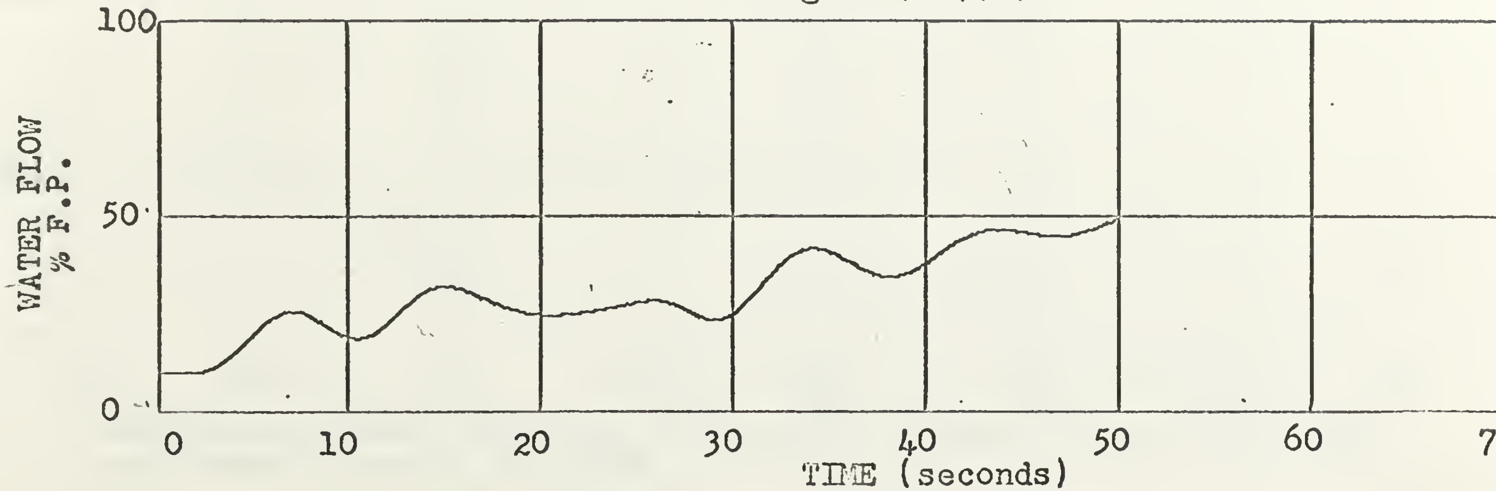
WATER FLOW vs TIME for the DLG-9 Model Boiler with Cruising Condition Transfer Functions

Figure 7-17(b)



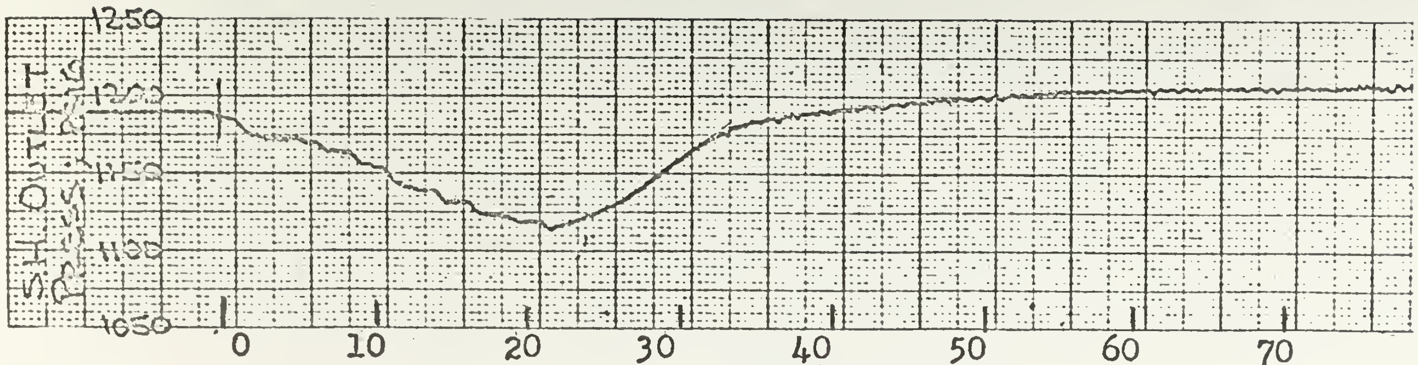
Water Flow vs Time for the DLG-9 Model Boiler with 90 per cent Transfer Functions

Figure 7-17(c)



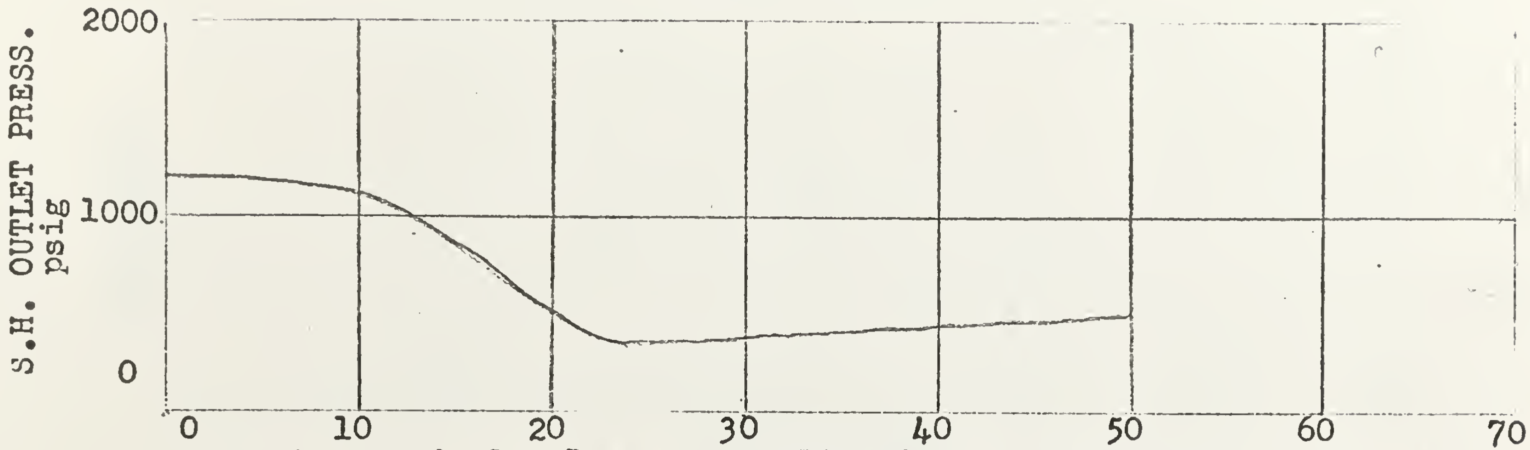
Water Flow vs Time for the DLG-9 Model Boiler with non linear Transfer Functions

Figure 7-17(d)



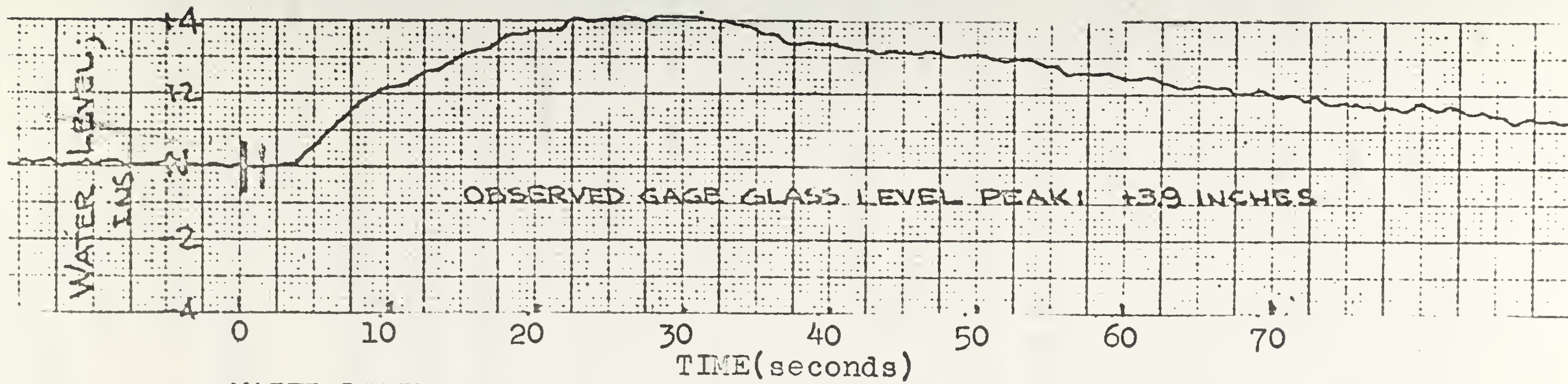
Superheater Outlet Pressure vs Time for the actual DLG-9 Boiler

Figure 7-18(a)



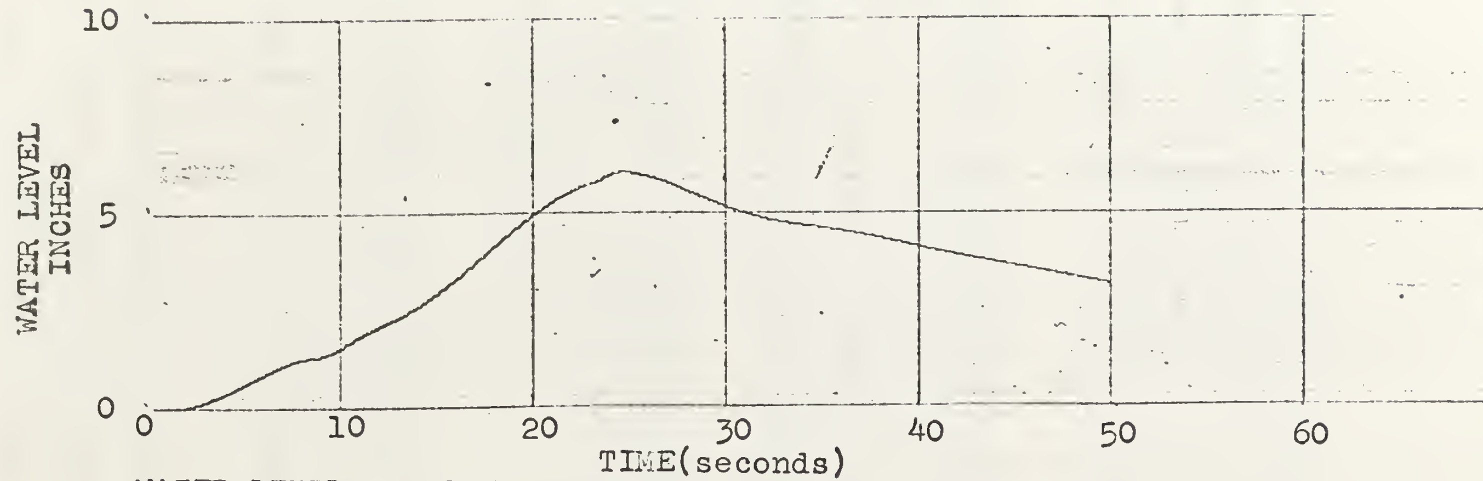
Superheater Outlet Pressure vs Time for the Model DLG-9 Boiler with non linear transfer functions

Figure 7-18(b)



WATER LEVEL vs TIME for the actual DLG-9 Boiler

Figure 7-19(a)



WATER LEVEL vs TIME for the DLG-9 Model Boiler with non linear Transfer Functions

Figure 7-19(b)

full power conditions the peak was 4.8 inches. These peaks of water level for the actual and for the three various simulations all occurred at 25 seconds.

7.4 Discussion of Results

The test results for the simulation of the complete boiler with the boiler transfer functions dependent upon the steam flow of the boiler show that this is not a good simulation of the actual boiler. The pressure changes are excessive and other responses in general do not compare favorably to the responses of the actual boiler.

Simulation of the boiler using the cruising conditions for the boiler transfer functions may be accurate in the range of five per cent around the cruising conditions set points, but is not very good for large perturbations, namely from ten to 90% full power as noted by the results of these simulations.

For large changes in steam flow the 90% full power transfer functions appear, from the results, to be the best data available with which to simulate the complete boiler for large perturbations.

7.5 Recommendations

The authors recommend that the original data recorded for the dynamics of the water system at NBTL [1] and the simulation attempted in this thesis be closely compared in order to find the cause of the oscillations in this simulation.

It is further recommended that data be obtained at ten per cent full power and at about 60 per cent full power in order to have a more accurate description of the boiler in a change from ten to 90% full power.

From the digital computer program results,using boiler transfer functions as a function of the steam flow of the boiler, it was noted that

the steam pressure/steam flow section of the boiler was the major cause of the low superheater outlet pressure developed.

BIBLIOGRAPHY

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2. Byrne, E. R., A program for a general purpose digital computer to perform analog type simulations. Bell Telephone Company, 1963.

3. Banham, J. W. Jr., Drossapoulos, B., and Breslin, C. A. Babcock and Wilcox Company single furnace natural circulation boiler for DLG-9 class. NBTL Project report B-271, March, 1961.

4. Drossopoulos, B. A., Evaluation of Babcock and Wilcox Company horizontal steam separators for DLG- 26, 28, 32, 34. NBTL Project Report B-493, November, 1963.

5. United States Naval Postgraduate School, Use of Mitrovic's method in the analysis of a control system with two gain feedback non-linearities by H. M. Yockey, May, 1965.

Appendix I

Program ANALOG

```
      CALL ANALOG
      END

      SUBROUTINE ANALOG
      DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
     1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
     2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
     3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
     4 X(9,50),Y(9,50)
      COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
     1 Y4,Y5,Z,L,X,Y
    4 DO 1 M=1,99
      C(M)=0.0
      CO(M)=0.0
      COO(M)=0.0
      COOO(M)=0.0
    1 COOOO(M)=0.0
    3 DO 2 N=1,20
    2 T(N)=0.0
       C(99)=0.0
      LL=0
       DO 22 KK=700,900
       X5(KK)=0.0
   22 Y5(KK)=0.
      CALL INITCON
C     READ IN THE VARIABLES TO BE PRINTED
  700 FORMAT (I2)
      READ 700,NVAR
      KNVAR=NVAR+1
      DO 701 K=2,KNVAR
  701 READ 700,L(K)
C     READ IN THE NUMBER OF GRAPHS
C     READ IN THE GRAPH DATA AND TITLES
  200 FORMAT(I2,6A8)
       READ 200,NGRAPHS,(ITITLE(I),I=1,6)
       IF (NGRAPHS) 9001,9001,209
  209 GO TO (201,202,203,204,205),NGRAPHS
 1205 FORMAT(2I2,6A8)
  205 READ 1205,K5,L5,(MTITLE(I),I=7,12)
  204 READ 1205,K4,L4,(LTITLE(I),I=7,12)
  203 READ 1205,K3,L3,(KTITLE(I),I=7,12)
  202 READ 1205,K2,L2,(JTITLE(I),I=7,12)
  201 READ 1205,K1,L1,(ITITLE(I),I=7,12)
 9001 PRINT 900
  900 FORMAT(6X,4HTIME,30X,9HVARIABLES)
  901 FORMAT(20X,5I20)
      PRINT 901,(L(N),N=2,KNVAR)
C     STORING POINTS TO BE PLOTTED
```

```
C      C(99) IS PROBLEM TIME
  299 CALL DIAGRAM
  210 IF(NGRAPHS) 800,800,211
  211 IF(C(99)-T(6)) 800,812,812
  812  IF(901-LL) 800,800,810
  810 LL=LL+1
  811 GO TO(500,501,502,503,504),NGRAPHS
  504 X5(LL)=C(K5)
      Y5(LL)=C(L5)
  503 X4(LL)=C(K4)
      Y4(LL)=C(L4)
  502 X3(LL)=C(K3)
      Y3(LL)=C(L3)
  501 X2(LL)=C(K2)
      Y2(LL)=C(L2)
  500 X1(LL)=C(K1)
      Y1(LL)=C(L1)
      T(6)=T(6)+T(4)
  800 CONTINUE
C      PRINTING ROUTINE
      IF (NVAR) 736,736,799
  799 IF (C(99)-T(8)) 704,705,705
  705 GO TO(711,712,713,714,715,716,717,718,719,720,721,722,723,724,
     1725,726,727,728,729,730,731,732,733,734,735),NVAR
  735 Z(26)=C(L(26))
  734 Z(25)=C(L(25))
  733 Z(24)=C(L(24))
  732 Z(23)=C(L(23))
  731 Z(22)=C(L(22))
  730 Z(21)=C(L(21))
  729 Z(20)=C(L(20))
  728 Z(19)=C(L(19))
  727 Z(18)=C(L(18))
  726 Z(17)=C(L(17))
  725 Z(16)=C(L(16))
  724 Z(15)=C(L(15))
  723 Z(14)=C(L(14))
  722 Z(13)=C(L(13))
  721 Z(12)=C(L(12))
  720 Z(11)=C(L(11))
  719 Z(10)=C(L(10))
  718 Z(09)=C(L(09))
  717 Z(08)=C(L(08))
  716 Z(07)=C(L(07))
  715 Z(06)=C(L(06))
  714 Z(05)=C(L(05))
  713 Z(04)=C(L(04))
  712 Z(03)=C(L(03))
  711 Z(02)=C(L(02))
  902 FORMAT(F15.9)
      PRINT 902,C(99)
  903 FORMAT(20X,5E20.6)
      PRINT 903,(Z(N),N=2,KNVAR)
  904 FORMAT(///)
```

```
 910 PRINT 904
     T(8)=T(8)+T(3)
 704 CONTINUE
 736 IF(T(2)-C(99)) 1000,1000,2000
2000 C(99)=C(99)+T(1)
     GO TO 299
1000  LAB=4H
 850 IF(NGRAPHS) 890,890,851
 851 GO TO(861,862,863,864,865),NGRAPHS
 865 DO 1865 I=1,6
1865 MTITLE(I)=ITITLE(I)
2865 CALL DRAW(LL,X5,Y5,0,0,LAB   ,MTITLE,0,0,1,1,0,0,7,2 ,1,LAST)
 864 DO 1864 I=1,6
1864 LTITLE(I)=ITITLE(I)
2864 CALL DRAW(LL,X4,Y4,0,0,LAB   ,LTITLE,0,0,1,1,0,0,7,2 ,1,LAST)
 863 DO 1863 I=1,6
1863 KTITLE(I)=ITITLE(I)
2863 CALL DRAW(LL,X3,Y3,0,0,LAB   ,KTITLE,0,0,1,1,0,0,7,2 ,1,LAST)
 862 DO 1862 I=1,6
1862 JTITLE(I)=ITITLE(I)
2862 CALL DRAW(LL,X2,Y2,0,0,LAB   ,JTITLE,0,0,1,1,0,0,7,2 ,1,LAST)
      MOD=0
 861 CALL DRAW(LL,X1,Y1,MOD,0,LAB ,ITITLE,0,0,1,1,0,0,7,8 ,1,LAST)
 890 GO TO 4
     RETURN
     END
     SUBROUTINE INITCON
     DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
    1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
    2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
    3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
    4 X(9,50),Y(9,50)
     COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
    1 Y4,Y5,Z,L,X,Y
C    READ THE NUMBER OF BLOCKS AND CHECK FOR FUNCTION GENERATOR
  10 FORMAT (1H1)
      PRINT 10
  20 FORMAT(I3)
     READ 20,NB
      NA=XABSF(NB)
  21 FORMAT(2H N,10X,2H G,13X,2H H,13X,2H P,13X,2H Q,13X,2H R)
     PRINT 21
C    READ IN THE BLOCK DATA
  50 FORMAT(I2,5E10.4)
     DO 60 J=1,NA
      READ 50,N,(G(N),H(N),P(N),Q(N),R(N))
  51 FORMAT(1H0,I2,5E15.5)
  60 PRINT 51,N,G(N),H(N),P(N),Q(N),R(N)
      PRINT 10
C    TEST TO SEE IF NB WAS MINUS
     IF(NB-NA)30,40,30
  40 PRINT 45
  45 FORMAT(34H THERE ARE NO CURVES TO BE READ IN)
     GO TO 100
```

```
C     READ IN THE NUMBER OF FUNCTION GENERATORS
   30 READ 70,NFG
  70  FORMAT(I1)
C     READ THE DATA FOR EACH FUNCTION GENERATOR
      DO 80 K=1,NFG
C     READ IN THE  NUMBER OF BREAKPOINTS
       PRINT 10
   81 FORMAT(I2)
      READ 81,NBKP
C     READ IN THE BREAK POINTS
   85 FORMAT(2E20.5)
      READ 85 (X(K,J),Y(K,J),J=1,NBKP)
   86 FORMAT (13H CURVE NUMBER,I2)
      PRINT 86,K
   87 FORMAT(I2,X,12HBREAK POINTS)
      PRINT 87,NBKP
   80 PRINT 85 (X(K,J),Y(K,J),J=1,NBKP)
C     READ THE NUMBER OF INITIAL CONDITION CARDS
       PRINT 10
  100 READ 110,NINC
  110 FORMAT(I3)
       IF (NINC) 111,140,111
  111 KNINC=XABSF(NINC)
C     READ IN THE INITIAL CONDITIONS AND PRINT THEM
      DO 120 M=1,KNINC
  115 FORMAT(I2,E20.6)
  120 READ 115,N,C(N)
C     CHECK TO SEE IF INVAL ROUTINE IS TO BE CALLED
      IF(NINC-KNINC)130,140,130
  145 FORMAT(38H NO INITIAL VALUE SUBROUTINE WAS USED ,////)
  140 PRINT 145
      GO TO 149
  130 CALL INVAL
  149  PRINT 147
  147 FORMAT(28H  C(N)   INITIAL CONDITIONS )
  150  DO 160 N=1,99
      IF(C(N))155,160,155
  116 FORMAT(2X,I2,E20.6,//)
  155 PRINT 116,N,C(N)
      CO(N)=C(N)
      COO(N)=C(N)
      COOO(N)=C(N)
      COOOO(N)=C(N)
  160 CONTINUE
C     READ IN THE TIME INCREMENTS T(1) IS THE TIME INCREMENT,T(2) IS TH
C     TOTAL TIME OF THE RUN,T(3) IS THE TIME INCREMENTS FOR PRINT OUTS,
C     T(4) IS THE TIME BETWEEN PLOT POINTS
  170 FORMAT(F10.5)
      READ 170,T(1)
      READ 170,T(2)
      READ 170,T(3)
      READ 170,T(4)
  200 FORMAT(/////)
       PRINT 200
```

```
210 FORMAT (9X,9H TIME INC,11X,14H LENGTH OF RUN,6X,
   1 15H PRINT TIME INC,5X,14H PLOT TIME INC )
211 FORMAT (4F20.8)
212 FORMAT(//)
      PRINT 210
      PRINT 212
      PRINT 211, T(1),T(2),T(3),T(4)
      PRINT 10
     RETURN
     END
      SUBROUTINE INVAL
     DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
    1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900)
    2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
    3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
    4 X(9,50),Y(9,50)
     COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
    1 Y4,Y5,Z,L,X,Y
      P(99)=0.0
      RETURN
      END
     SUBROUTINE ADVANCE(N,I,J)
     DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
    1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900)
    2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
    3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
    4 X(9,50),Y(9,50)
     COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
    1 Y4,Y5,Z,L,X,Y
     COOOO(I)=COOO(I)
     COOO(I)=COO(I)
     COO(I)=CO(I)
     CO(I)=C(I)
     C(I)=1.4375*C(J)+.25*CO(J)-.625*COO(J)-.25*COOO(J)+.1875*COOOO(J
     RETURN
     END
     SUBROUTINE DERIVA(N,I,J)
     DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
    1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900)
    2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
    3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
    4 X(9,50),Y(9,50)
     COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
    1 Y4,Y5,Z,L,X,Y
     COOOO(I)=COOO(I)
     COOO(I)=COO(I)
     COO(I)=CO(I)
     CO(I)=C(I)
     C(I)=(G(N)/T(1))*(.5*COO(J)-2.0*CO(J)+1.5*C(J))
     RETURN
     END
     SUBROUTINE INPUT(N,I)
     DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
    1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900)
```

```
 2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
 3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
 4 X(9,50),Y(9,50)
  COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
 1 Y4,Y5,Z,L,X,Y
  COOOO(I)=COOO(I)
  COOO(I)=COO(I)
  COO(I)=CO(I)
  CO(I)=C(I)
C G(N) IS THE VALUE OF THE STEP,H(N)-THE SLOPE OF THE RANP,
C P(N)-AMPLITUDE OF THE SIN WAVE,Q(N)-W(FREQUENCY) OF THE SIN WAVE
  IF (Q(N)) 1,2,1
1 SINE=P(N)*SINF(Q(N)*C(99))
  GO TO 3
2 SINE=0.0
3 C(I)=G(N)+H(N)*C(99)+SINE
  RETURN
  END
  SUBROUTINE REALPL(N,I,J)
  DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
 1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900)
 2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
 3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
 4 X(9,50),Y(9,50)
  COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
 1 Y4,Y5,Z,L,X,Y
  COOOO(I)=COOO(I)
  COOO(I)=COO(I)
  COO(I)=CO(I)
  CO(I)=C(I)
   IF (H(N)) 1,2,1
2 C(I)=G(N)*T(1)*CO(J)+CO(I)
   GO TO 3
1 CONTINUE
  A=EXPF(-H(N)*T(1))
  B=T(1)*H(N)*H(N)/G(N)
  C(I)=CO(J)*( (1.-A)/B-A*G(N)/H(N))+C(J)*(G(N)/H(N)-(1.-A)/B) +
 1CO(I)*A
3 CONTINUE
  RETURN
  END
   SUBROUTINE LIMITER (N,I,J)
  DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
 1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900)
 2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
 3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
 4 X(9,50),Y(9,50)
  COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
 1 Y4,Y5,Z,L,X,Y
  COOOO(I)=COOO(I)
  COOO(I)=COO(I)
  COO(I)=CO(I)
  CO(I)=C(I)
  C(I)=G(N)*C(J)
```

```
C     CHECK UPPER LIMIT,THEN LOWER LIMIT
      IF(C(I)-H(N))10,10,20
   10 IF(P(N)-C(I))40,40,30
   20 C(I)=H(N)
      GO TO 40
   30 C(I)=P(N)
   40 RETURN
      END
      SUBROUTINE MAGNITD(N,I,J)
      DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
     1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
     2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
     3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
     4 X(9,50),Y(9,50)
      COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
     1 Y4,Y5,Z,L,X,Y
      COOOO(I)=COOO(I)
      COOO(I)=COO(I)
      COO(I)=CO(I)
      CO(I)=C(I)
      C(I)=ABSF(C(J))
      RETURN
      END
      SUBROUTINE IDRELAY(N,I,J)
      DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
     1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
     2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
     3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
     4 X(9,50),Y(9,50)
      COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
     1 Y4,Y5,Z,L,X,Y
      COOOO(I)=COOO(I)
      COOO(I)=COO(I)
      COO(I)=CO(I)
      CO(I)=C(I)
      IF(C(J)) 10,15,20
C     SUBSTITUTE LOWER LIMIT
   10 C(I)=H(N)
      GO TO 30
   15 C(I)=0.
      GO TO 30
C     SUBSTITUTE UPPER LIMIT
   20 C(I)=G(N)
   30 CONTINUE
      RETURN
      END
      SUBROUTINE GAIN(N,I,J)
      DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
     1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
     2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
     3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
     4 X(9,50),Y(9,50)
      COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
     1 Y4,Y5,Z,L,X,Y
```

```
      COOOO(I)=COOO(I)
      COOO(I)=COO(I)
      COO(I)=CO(I)
      CO(I)=C(I)
      C(I)=G(N)*C(J)
      RETURN
      END
      SUBROUTINE MULTPLY(N,I,J,K)
      DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
     1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
     2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
     3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
     4 X(9,50),Y(9,50)
      COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
     1 Y4,Y5,Z,L,X,Y
      COOOO(I)=COOO(I)
      COOO(I)=COO(I)
      COO(I)=CO(I)
      CO(I)=C(I)
      C(I)=C(J)*C(K)
      RETURN
      END
      SUBROUTINE DIVIDE(N,I,J,K)
      DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
     1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
     2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
     3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
     4 X(9,50),Y(9,50)
      COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
     1 Y4,Y5,Z,L,X,Y
      COOOO(I)=COOO(I)
      COOO(I)=COO(I)
      COO(I)=CO(I)
      CO(I)=C(I)
      C(I)=C(J)/C(K)
      RETURN
      END
      SUBROUTINE CURVE(NO,I,J)
      DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
     1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
     2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
     3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
     4 X(9,50),Y(9,50)
      COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
     1 Y4,Y5,Z,L,X,Y
      COOOO(I)=COOO(I)
      COOO(I)=COO(I)
      COO(I)=CO(I)
      CO(I)=C(I)
C     THIS IS A LINEAR INTERPOLATION USING THE FORMULA
C     C(I)=YO-(YO-YN)(C(J)-XO)/(XN-XO)
       K=0
   15 K=K+1
      IF(51-K) 30,30,1
```

```
 1 IF(C(J)-X(NO,K)) 10,20,15
10 IF(K-1) 30,30,2
 2 C(I)=Y(NO,K-1)-(Y(NO,K-1)-Y(NO,K))*(C(J)-X(NO,K-1))/
  1 (X(NO,K)-X(NO,K-1))
   GO TO 6
30 PRINT 4,NO
 4 FORMAT(30HFUNCTION GENERATOR ERROR CURVE,I2)
   PRINT 5,J,C(J)
 5 FORMAT(3H X(,I3,3H )=,E20.5)
   STOP
20 C(I)=Y(NO,K)
 6 RETURN
   END
   SUBROUTINE RECIP  (N,I,J)
   DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
  1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
  2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
  3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
  4 X(9,50),Y(9,50)
   COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
  1 Y4,Y5,Z,L,X,Y
   COOOO(I)=COOO(I)
   COOO(I)=COO(I)
   COO(I)=CO(I)
   CO(I)=C(I)
   C(I)=G(N)/C(J)
   RETURN
   END
   SUBROUTINE DELAY(N,I,J)
   DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
  1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
  2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
  3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
  4 X(9,50),Y(9,50)
   COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
  1 Y4,Y5,Z,L,X,Y
   COOOO(I)=COOO(I)
   COOO(I)=COO(I)
   COO(I)=CO(I)
    CO(I)=C(I)
   IF(C(99)-G(N)) 10,20,20
10 C(I)=0.0
   GO TO 30
20 C(I)=C(J)
30 CONTINUE
   RETURN
   END
   SUBROUTINE ADDER(N,I,J,K,LK)
   DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
  1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
  2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
  3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
  4 X(9,50),Y(9,50)
   COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
```

```
 1 Y4,Y5,Z,L,X,Y
   COOOO(I)=COOO(I)
   COOO(I)=COO(I)
   COO(I)=CO(I)
   CO(I)=C(I)
   IF(J) 1,3,3
 1 JJ=XABSF(J)
    S1=-C(JJ)
   GO TO 4
 3 S1=C(J)
 4 IF(K) 5,6,6
 5 KK=XABSF(K)
    S2=-C(KK)
   GO TO 7
 6 S2=C(K)
 7 IF(LK)8,9,10
 8 LL=XABSF(LK)
    S3=-C(LL)
    GO TO 11
10 S3=C(LK)
11 C(I)=S1+S2+S3
   GO TO 15
 9 C(I)=S1+S2
15 CONTINUE
   RETURN
   END
   SUBROUTINE DELAY1(N,I,J)
   DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
  1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
  2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
  3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
  4 X(9,50),Y(9,50) ,A(3,1002) ,M(5)
   COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
 1 Y4,Y5,Z,L,X,Y
    IF (C(99)-T(1)) 2,1,1
 2 DO 5 KK=1,3
   DO 5 JJ=1,1001
 5 A(KK,JJ)=C(I)
    H(N)=G(N)/T(1)+2.
     M(N)=H(N)
 1 COOOO(I)=COOO(I)
   COOO(I)=COO(I)
   COO(I)=CO(I)
   CO(I)=C(I)
    MM=M(N)
    A(N,MM)=C(J)
    DO 3 K=1,MM
 3 A(N,K)=A(N,K+1)
   C(I)=A(N,1)
   RETURN
   END
   SUBROUTINE NOISE(N,I)
   DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
  1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
```

```
2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
4 X(9,50),Y(9,50)
 COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
1 Y4,Y5,Z,L,X,Y
 COOOO(I)=COOO(I)
 COOO(I)=COO(I)
 COO(I)=CO(I)
 CO(I)=C(I)
 CALL RNDEV(1220703125,DEV)
 C(I)=H(N)*DEV+G(N)
 RETURN
 END
  SUBROUTINE ERROR (N,K,I,J)
 DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
4 X(9,50),Y(9,50)
 COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
1 Y4,Y5,Z,L,X,Y
   THIS ROUTINE SUMS(C(I)-C(J))**2(DT) OVER T AND DIVIDES BY T
  IF(C(99)-T(1)) 2,1,2
1 ERR=0.0
2 ERR=ERR+((C(I)-C(J))**2)*T(1)
   C(N)=ERR/C(99)
   C(K)=C(I)-C(J)
  IF(C(99)-T(2))5,3,3
6 FORMAT (1H1)
  PRINT 6
3 ERX=ERR/T (2)
4 FORMAT(11HTHE NUMBER ,I2,10H ERROR IS ,F20.9)
  PRINT 4,N,ERX
5 RETURN
  END
  SUBROUTINE CMPLXPL (N,I,J)
  DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
 1COOO(99),COOOO(99),T(20),X1(900),X2(900),X3(900),X4(900),X5(900),
 2Y1(900),Y2(900),Y3(900),Y4(900),Y5(900),Z(26),L(26),
 3ITITLE(12),JTITLE(12),KTITLE(12),LTITLE(12),MTITLE(12),
 4 X(9,50),Y(9,50),AK(4,2),YC(2),DY(2)
  COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X4,X5,Y1,Y2,Y3,
 1 Y4,Y5,Z,L,X,Y
  COOOO (I)=COOO(I)
  COOO(I)=COO(I)
  COO(I)=CO(I)
  CO(I)=C(I)
  Y5(700+2*N)=G(N)*CO(J)-H(N)*X5(700+2*N)-P(N)*CO(I)
  X5(700+2*N)=Y5(700+2*N)*T(1)+X5(700+2*N)
   C(I)=X5(700+2*N)*T(1)+CO(I)
  RETURN
  END
```

Appendix II

Root Locus Program

```
      PROGRAM RLOCUS
      PROGRAMMERS RM NUTTING , JL FENICK , AND JA POPE
      THIS PROGRAM WILL PLOT A ROOT LOCUS FOR A CHARACTERISTIC EQUATION UP TO
      ORDER 30. ROOT LOCUS POLES ARE PLOTTED WITH AN X, ROOT LOCUS ZEROS ARE
      PLOTTED WITH A SQUARE, AND INTERMEDIATE ROOT POINTS ARE PLOTTED WITH A
      PLUS. THE STARTING VALUE OF ROOT LOCUS GAIN AND THE NUMBER OF DECADES
      TO BE SPANNED BY THE GAIN MUST BE SPECIFIED. THE GRAPH PLOT IS BASED ON
      PLOTTING EVERY TENTH POINT AS THE GAIN VARIES BETWEEN ITS INITIAL AND
      FINAL VALUE IN 300 STEPS.
            THE DATA CARDS ARE SUBMITTED IN THE FOLLOWING MANNER. SUBMIT A
      COMPLETE SET OF DATA CARDS FOR EACH ROOT LOCUS TO BE PLOTTED.
      CARD 1  THE FIRST LINE OF THE GRAPH TITLE  (IN COLUMNS 1-48)
      CARD 2  THE SECOND LINE OF THE GRAPH TITLE  (IN COLUMNS 1-48)
      CARD 3 THE ORDER OF THE CHARACTERISTIC EQUATION (I2 FORMAT)
      CARD 4 CONSTANT COEFFICIENTS IN DESCENDING ORDER. (8E10.5 FORMAT)
      CARD 5 COEFFICIENTS OF THE VARIABLE IN DESCENDING ORDER (8E10.5 FORMAT)
      CARD 6 INITIAL VALUE OF THE VARIABLE ( E10.5 FORMAT) , MUST NOT BE ZERO
      CARD 7 NUMBER OF DECADES TO BE SPANNED. (FROM 1-10) , (I2 FORMAT)
      CARD 8 GRAPH SCALE TO ONE SIGNIFICANT FIGURE. (E10.5 FORMAT)
      DIMENSION R(129),X(129),IT(10),ROOTR(128),ROOTI(128),ITITLE(12),
     1A(129),B(129),ROOTJ(128),ROOTM(128)
      COMMON R,VAR,NO,ROOTR,ROOTI
      DO 15 K=1,129
   15 X(K)=0.0
  206 MOD=1
      LAB=4H
      MM=0
      DO 14 L=1,10
   14 IT=8H
  200 FORMAT(6A8)
  203 FORMAT(I2)
  204 FORMAT(E10.5)
      READ 200,(ITITLE(I),I=1,6)
      READ 200,(ITITLE(I),I=7,12)
   24 FORMAT(1H1,////,17HTHE INPUT DATA IS,////)
      PRINT 24
   28 FORMAT(///,36HORDER OF THE CHARACTERISTIC EQUATION,///)
      PRINT 28
      READ 203,NO
      PRINT 203,NO
      N=NO+1
  205 FORMAT(8E10.5)
  207 FORMAT (8E12.5)
   22 FORMAT(///,41HCONSTANT COEFFICIENTS IN DESCENDING ORDER,///)
      PRINT 22
      READ 205,(A(K),K=1,N)
      PRINT 207,(A(K),K=1,N)
   23 FORMAT(///,48HCOEFFICIENTS OF THE VARIABLE IN DESCENDING ORDER,
```

```
  1///)
   PRINT 23
   READ 205,(B(K),K=1,N)
   PRINT 207,(B(K),K=1,N)
 25 FORMAT(///,29HINITIAL VALUE OF THE VARIABLE,///)
   PRINT 25
   READ 204,VAR
   PRINT 204,VAR
 26 FORMAT(///,31HNUMBER OF DECADES TO BE SPANNED,///)
   PRINT 26
   READ 203,ND
   PRINT 203,ND
 27 FORMAT(///,5HSCALE,///)
   PRINT 27
   READ 204,XSCALE
   PRINT 204,XSCALE
   YSCALE=XSCALE
201 FORMAT(21H1THE SYSTEM POLES ARE,////)
   PRINT 201
   CALL ROOTS2 (A,X,NO,IT,ROOTR,ROOTI,MM,-.5,+.5)
   CALL DRAW(NO,ROOTR,ROOTI,MOD,1,LAB,ITITLE,XSCALE,YSCALE,
  11,6,2,2,7,8,1,LAST)
   MOD=2
202 FORMAT(//,21H THE SYSTEM ZEROS ARE,///)
   K=1
  3 IF(B(K)) 1,2,1
  2 K=K+1
   GO TO 3
  1 NORD=N-K
   IF(NORD-1) 6,4,5
  4 ZERO=-B(K+1)/B(K)
  7 FORMAT(//,16HTHE SYSTEM ZERO=,E10.5,///)
   PRINT 7,ZERO
   GO TO 8
  6 PRINT 9
  9 FORMAT(//,25HALL ZEROS ARE AT INFINITY)
   GO TO 8
  5 NN=NORD+1
   DO 10 L=1,NN
   R(L)=B(K)
 10 K=K+1
   PRINT 202
   CALL ROOTS2 (R,X,NORD,IT,ROOTM,ROOTJ,MM,-.5,+.5)
   CALL DRAW(NORD,ROOTM,ROOTJ,MOD,3,LAB,ITITLE,XSCALE,YSCALE,
  11,6,2,2,7,8,1,LAST)
   MOD=2
  8 CONTINUE
   GO TO(31,32,33,34,35,36,37,38,39,40),ND
 31 G=1.0076
   GO TO 41
 32 G=1.016
   GO TO 41
 33 G=1.0245
   GO TO 41
```

```
 34 G=1.0312
    GO TO 41
 35 G=1.0394
    GO TO 41
 36 G=1.0483
    GO TO 41
 37 G=1.0568
    GO TO 41
 38 G=1.0633
    GO TO 41
 39 G=1.071
    GO TO 41
 40 G=1.078
 41 PRINT 30
 30 FORMAT(1H1,////,61HROOTS FOR THE SPECIFIED VALUES OF THE VARIABLE
   1ARE AS FOLLOWS,////)
    PRINT 42
 42 FORMAT(10X,4H VAR,4X,9HREAL PART,3X,9HIMAG PART,
   113X,9HREAL PART,3X,9HIMAG PART,13X,9HREAL PART,3X,9HIMAG PART,///)
    DO 101 J=1,30
    DO 100 K=1,10
 60 FORMAT(1PE12.3)
    PRINT 60,VAR
    DO 300 L=1,N
300 R(L)=A(L)+B(L)*VAR
 50 FORMAT(15X,3(1P2E12.3,10X))
    CALL ROOTX
    DO 71 JJ=1,NO
    IF(ABSF(ROOTI(JJ))-5.E-04) 69,69,70
 69 ROOTJ(JJ)=0.
    GO TO 71
 70 ROOTJ(JJ)=ROOTI(JJ)
 71 CONTINUE
    PRINT 50,(ROOTR(I),ROOTJ(I),I=1,NO)
100 VAR=G*VAR
    IF(J-1) 101,101,99
 99 MOD=2
    IF(J-30) 101,98,98
 98 MOD=3
101 CALL DRAW(NO,ROOTR,ROOTJ,MOD,2,LAB,ITITLE,XSCALE,YSCALE,
   1 1,6,2,2,7,8,1,LAST)
    GO TO 206
    END
    SUBROUTINE ROOTX
    DIMENSION C(31),D(29),R(129),ROOTR(128),ROOTI(128)
    COMMON R,VAR,NO,ROOTR,ROOTI
    M=1
 20 BETAN =ROOTI(M) +.001
    ALFAN=ROOTR(M)
    DO 7 I=1,100
    S=2.*ALFAN
    T=-(ALFAN**2+BETAN**2)
    C(1)=R(1)
    C(2)=R(2)+S*R(1)
```

```
      NC=NO+1
      DO 2 L=3,NC
    2 C(L) = R(L)+S*C(L-1) + T*C(L-2)
      AN= C(NO+1)-ALFAN*C(NO)
      BN= BETAN*C(NO)
      IF (NO-3) 21, 17, 18
   17 CN = 3.*R(1)*(ALFAN**2-BETAN**2) + 2.*R(2)*ALFAN + R(3)
      DN = 6.*R(1)*ALFAN*BETAN + 2.*R(2)*BETAN
      GO TO 19
   21 CN = 2.*R(1)*ALFAN + R(2)
      DN  = 2.*R(1)*BETAN
      GO TO 19
   18 D(1) = C(1)
      D(2)=C(2)+S*D(1)
      NU=NO-1
      DO 3 N=3,NU
    3 D(N)=C(N)+S*D(N-1)+T*D(N-2)
      CN= C(NO)-2.*D(NO-2)*BETAN**2
      DN= 2.*BETAN*(D(NO-1)-ALFAN*D(NO-2))
   19 ALFA=ALFAN-(AN*CN+BN*DN)/(CN**2+DN**2 )
      BETA=BETAN+(AN*DN-BN*CN)/(CN**2+DN**2)
      IF (ABSF(ALFA-ALFAN)-5.E-4) 4,4,5
    4 IF(ABSF(BETA-BETAN)-5.E-4)    6,6,5
    5 ALFAN=ALFA
    7 BETAN=BETA
      PRINT 50
   50 FORMAT (46H NO CONVERGENCE IN100 ITERATIONS AT THIS GAIN )
      GO TO 12
    6 ROOTR(M)=ALFA
    1 ROOTI(M)=BETA
      IF (ABSF(ROOTI(M))-5.E-4) 12,12,13
   13 ROOTR(M+1) = ROOTR(M)
      ROOTI(M+1) = -ROOTI(M)
      M=M+1
   12 IF(M-NO) 15,16,16
   15 M=M+1
      GO TO 20
   16 RETURN
      END
      END
```

Appendix III

Subroutines INVAL and DIAGRAM and Data for Cruising Conditions and Ninety Per Cent Delta Plant

```
      SUBROUTINE INVAL
      DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
     1COOO(99),COOOO(99),T(10),X1(900),X2(900),X3(900),
     2Y1(900),Y2(900),Y3(900),
     3ITITLE(12),JTITLE(12),KTITLE(12),
     4 X(9,50),Y(9,50)
      COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X,Y,Y1,Y2,Y3
C     C(50) IS READ FROM IC CARD
       C(42)=15900.
       C(97)=15.
      C(92)=C(50)
      CALL CURVE (2,47,50)
      CALL CURVE (1,76,50)
      CALL ADDER (48,48,76,23,-47)
      C(77)=0.04*C(48)-33.0
      C(49)=C(77)
      C(52)=C(97)-C(49)
      C(53)=(G(53)/H(53))*C(52)
      C(78)=0.0001142 *C(50)+3.0
      C(57)=C(78)
      C(54)=C(53)+C(57)
      C(55)=C(54)
      C(67)=C(55)
      C(66)=C(67)-3.0
      C(3)=C(66)*(H(66)/G(66))
      C(65)=C(3)
      C(79)=C(65)
      C(75)=C(79)/.254
      C(72)=C(75)/G(75)
      C(56)=C(55)-C(67)
      C(70)=C(72)*(H(72)/G(72))
      C(69)=C(70)
      C(63)=C(69)*(H(69)/G(69))
      C(61)=C(63)
      C(60)=C(61)
      C(58)=C(56)*(G(58)/P(58))
      C(51)=C(58)*G(51)
      C(59)= C(60)-C(51)
      IF(C(55)-C(67))1,1,2
    1 C(64)=C(55)
      GO TO 3
    2 C(64)=C(67)
    3 CONTINUE
C     FUEL OIL FLOW (GF) FOR CRUISING SPEED =4140.
      C(46)=C(64)-3.0
      C(45)=C(46)*H(46)/G(46)
      C(39)=C(45)/0.00141
      C(41)=C(42)-G(40)*C(39)
      C(40)=C(39)*G(40)
      C(90)=C(39)
      C(38)=C(41)-C(39)
       C(87)=C(38)
      C(80)= C(38)*0.00141 +3.0
      C(81)=0.00141*C(41)+3.0
      C(44)=C(81)
      C(43)=C(80)
      C(5)=C(14)+15.0
      C(33)=C(5)
      C(93)=C(50)
      C(4)=0.000114*C(93)+3.0
```

```
C(29)=C(4)
C(30)=C(29)
C(31)=C(57)-C(30)
C(32)=C(31)*(G(32)/H(32))
C(24)=C(97)+C(32)-C(33)
C(25)=C(24)*(G(25)/P(25))
RETURN
 END
```

```
      SUBROUTINE DIAGRAM
      DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
     1COOO(99),COOOO(99),T(10),X1(900),X2(900),X3(900),
     2Y1(900),Y2(900),Y3(900),
     3ITITLE(12),JTITLE(12),KTITLE(12),
     4 X(9,50),Y(9,50)
      COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X,Y,Y1,Y2,Y3
       IF(C(99)-5.0)10,10,20
   10 C(50)=56000.-(600.*C(99))
   20 CONTINUE
      CALL CURVE (2,47,50)
      CALL CURVE (1,76,50)
      CALL ADDER (48,48,76,23,-47)
        CO(77)=C(77)
      C(77)=.04*C(48)-33.0
      CALL CMPLXPL(49,49,77)
       C(97)=15.
      CALL ADDER (52,52,97,-49,0)
      CALL REALPL (53,53,52)
       CO(78)=C(78)
      C(78)=.0001142*C(50)+3.0
      CALL CMPLXPL(57,57,78)
      CALL ADDER (54,54,53,57,0)
      CALL CMPLXPL (55,55,54)
      CALL ADDER (56,56,55,-67,0)
      CALL CMPLXPL (58,58,56)
      CALL GAIN (51,51,58)
      IF(C(51)-30.0  )1000,1000,2000
 1000 IF(C(51)-0.0)3000,3000,4000
 2000 C(51)=30.0
      GO TO 4000
 3000 C(51)=0.0
 4000 CONTINUE
      CALL REALPL (59,59,58)
      IF(C(59)-30.0)1100,1100,2100
 1100 IF(C(59)-0.0)3100,3100,4100
 2100 C(59)=30.0
      GO TO 4100
 3100 C(59)=0.0
 4100 CONTINUE
      CALL ADDER(60,60,51,59,0)
       IF (C(60)-30.) 1200,1200,2200
 1200 IF(C(60)-0.) 3200,3200,4200
 2200 C(60)=30.
       GO TO 4200
 3200 C(60)=0.
 4200 CONTINUE
      CALL CMPLXPL (61,61,60)
      CALL DERIVA (62,62,61)
      CALL ADDER (63,63,61,62,0)
C     THE AIR SYSTEM GOES HERE
      CALL REALPL (69,69,63)
      CALL CMPLXPL (70,70,69)
      CALL REALPL (72,72,70)
      CALL GAIN (75,75,72)
       CO(79)=C(79)
      C(79)=C(75) *.254
      CALL REALPL(65,65,79)
      CALL DELAY1 (3,3,65)
      CALL REALPL (66,66,3)
```

```
      C(67)=C(66) +3.0
      IF(C(55)-C(67))1,1,2
    1 C(64)=C(55)
      GO TO 3
    2 C(64)=C(67)
    3 CONTINUE
C     OIL SYSTEM GOES HERE
      CO(34)=C(34)
      C(34)=C(64)-(C(46)+3.0)
      CALL REALPL(35,35,34)
      CALL GAIN (36,36,34)
      CALL ADDER (37,37,35,36,0)
       CALL REALPL (86,86,37)
      CALL ADDER(38,38,-86,87,0)
      CALL ADDER(39,39,-38,41,0)
      CALL ADDER(89,89,39,-90,0)
      CALL GAIN(40,40,39)
      CALL ADDER(41,41,-40,42,0)
       CO(81)=C(81)
       CO(80)=C(80)
      C(80)= C(38)*0.00141 +3.0
      C(81)=0.00141*C(41)+3.0
      CALL CMPLXPL(43,43,80)
      CALL CMPLXPL(44,44,81)
      CALL ADDER (45,45,44,-43,0)
      CALL REALPL(46,46,45)
C   WATER SYSTEM
       CO(5)=C(5)
      C(5)=C(14)+15.0
      CALL CMPLXPL (33,33,5)
      CALL ADDER  (24,24,-33,32,97)
      CALL CMPLXPL(84,84,24)
      CALL GAIN(25,25,84)
      CALL REALPL(26,26,84)
      CALL ADDER (27,27,25,26,0)
      CALL DELAY1 (2,2,27)
      CALL CMPLXPL(28,28,2)
      CO(4)=C(4)
      C(4)=0.000114*(C(93)+C(28))+3.0
      CALL CMPLXPL(29,29,4)
      CALL REALPL  (30,30,29)
      CALL ADDER(31,31,57,-30,0)
      CALL REALPL (32,32,31)
C   WATER LEVEL
      CALL ADDER(91,91,50,-92,0)
      CALL REALPL(6,6,91)
      CALL REALPL(7,7,91)
      CALL CMPLXPL(8,8,7)
      CALL ADDER (9,9,8,-6,0)
      CALL REALPL (10,10,28)
      CALL CMPLXPL(11,11,10)
      CALL REALPL(12,12,89)
      CALL CMPLXPL(13,13,12)
      CALL DELAY1 (1,1,13)
      CALL ADDER (14,14,9,11,1)
C   STEAM PRESS
      CALL REALPL(83,83,91)
      CALL REALPL (15,15,83)
      CALL REALPL (16,16,15)
      CALL ADDER (17,17,15,-16,0)
```

```
      CALL REALPL(82,82,89)
      CALL REALPL(18,18,82)
      CALL REALPL (19,19,18)
      CALL ADDER (20,20,18,-19,0)
      CALL REALPL (21,21,28)
      CALL REALPL (22,22,21)
      CALL ADDER (23,23,20,-17,-22)
      RETURN
      END
```

```
C    DATA FOR CRUISING CONDITIONS DELTA PLANT

-48         NUMBER OF BLOCK DATA CARDS
01 0.8
02 0.25
03 0.045
06  1.12 -06
07 2.805 -05  0.3141
08  1.0       0.763      1.588
10  5.54- 07
11  1.0       0.422       0.495
12  1.86 -04   2.22
13  1.0       0.76        0.4
15  3.68 -04 .0445
16 1.382     1.41
18 7.87  -03 .0445
19 1.732     1.76
21 1.73  -06
22 1.0       0.0445
25 1.26
26 0.1
28 9360.      .531      .781
29  19.2     26.2       19.2
30 0.222      0.222
32 14.7       29.4
33  4.0       2.4        4.0
35 0.392
36 2.82
40 0.0445
43  30.3      5.9        30.3
44  30.3     5.9        30.3
46 30.87     29.4
49  50.0     .6         50.
51 .944
53 73.6      29.4
55 250.      9.5       250.
57 19.25     26.15      19.25
58  333.3     13.3       333.3
59 .106
61 100.      7.9        100.
62 .89
65 2.5       2.5
66 30.87      29.4
69 512.0      1.0
70 2.0       0.56       2.0
72 .000683    .1
75 1.134
82 1.0
83 1.0
84 1.25       0.675     1.25
86 24804.     31.2
2            NUMBER OF CURVES
09          BREAK PTS      BOILER PRESSURE        CURVE 1
   0.0                     1200.
  34000.                   1203.
  56000.                   1208.
```

```
  66500.                    1211.
  100000.                   1226.
  120000.                   1237.
  140000.                   1250.
  152000.                   1259.
  167000.                   1272.
44   BREAKPOINTS  SUPERHEATER PRESSURE DROP  CURVE 2
   0.0                          0.0
    20000.               1.0
  28000.               2.0
     34000.             3.0
   39000.                4.0
  45000.                         5.2
  48000.                        6.0
  50000.                        6.5
  52000.                        7.0
  54000.                        7.4
  56000.                        8.0
  58000.                        8.6
  60000.                    9.2
  62000.                   10.0
  64000.                   10.5
  66000.                   11.1
  68000.                   12.0
  70000.                   12.8
  74000.                   14.0
  76000.                   15.0
  78000.                   15.9
  80000.                   16.6
  84000.                   18.0
  86000.                   19.0
  88000.                   20.0
  90000.                   21.0
  94000.                   23.0
  96000.                   24.0
  98000.                   25.0
 100000.                   26.0
 108000.                   30.0
 117000.                   35.0
 120000.                   37.0
 125000.                   40.0
 130000.                   44.0
 140000.                   50.0
 145000.                   54.0
 150000.                   59.0
 160000.                   66.0
 165000.                   70.0
 170000.                   74.0
 180000.                   84.0
 190000.                   92.0
 200000.                  101.0
-01
50 56000.
0.01        TIME INCREMENT
55.0       TOTAL TIME
1.
0.2                     PLOT TIME
0193         VARIABLES TO BE PRINTED
03 OBRIEN GH DELTA SYSTEM LINEAR AIR (NEG RAMP)3-17
9975  AIR FLOW (C-75) (PERCENT) VS TIME
```

9989 DELTA FUEL FLOW (C-89) (LBS/HR) VS TIME (SEC)
9928 DELTA FEEDWATER FLOW (C-28) (LBS/HR) VS TIME

```
      SUBROUTINE DIAGRAM
      DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
     1COOO(99),COOOO(99),T(10),X1(900),X2(900),X3(900),
     2Y1(900),Y2(900),Y3(900),
     3ITITLE(12),JTITLE(12),KTITLE(12),
     4 X(9,50),Y(9,50)
      COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X,Y,Y1,Y2,Y3
       IF(C(99)-5.0)10,10,20
   10 C(50)=152000. -(1600. * C(99))
   20 CONTINUE
      CALL CURVE (2,47,50)
      CALL CURVE (1,76,50)
      CALL ADDER (48,48,76,23,-47)
        CO(77)=C(77)
      C(77)=.04*C(48)-33.0
      CALL CMPLXPL(49,49,77)
       C(97)=15.
      CALL ADDER (52,52,97,-49,0)
      CALL REALPL (53,53,52)
       CO(78)=C(78)
      C(78)=.0001142*C(50)+3.0
      CALL CMPLXPL(57,57,78)
      CALL ADDER (54,54,53,57,0)
      CALL CMPLXPL (55,55,54)
      CALL ADDER (56,56,55,-67,0)
      CALL CMPLXPL (58,58,56)
      CALL GAIN (51,51,58)
      IF(C(51)-30.0  )1000,1000,2000
 1000 IF(C(51)-0.0)3000,3000,4000
 2000 C(51)=30.0
      GO TO 4000
 3000 C(51)=0.0
 4000 CONTINUE
      CALL REALPL (59,59,58)
      IF(C(59)-30.0)1100,1100,2100
 1100 IF(C(59)-0.0)3100,3100,4100
 2100 C(59)=30.0
      GO TO 4100
 3100 C(59)=0.0
 4100 CONTINUE
      CALL ADDER(60,60,51,59,0)
       IF (C(60)-30.) 1200,1200,2200
 1200 IF(C(60)-0.) 3200,3200,4200
 2200 C(60)=30.
       GO TO 4200
 3200 C(60)=0.
 4200 CONTINUE
      CALL CMPLXPL (61,61,60)
      CALL DERIVA (62,62,61)
      CALL ADDER (63,63,61,62,0)
C     THE AIR SYSTEM GOES HERE
      CALL REALPL (69,69,63)
      CALL CMPLXPL (70,70,69)
      CALL REALPL (72,72,70)
      CALL GAIN (75,75,72)
      C(94)=C(75)*1.2
       CO(79)=C(79)
      C(79)=C(75) *.254
      CALL REALPL(65,65,79)
      CALL DELAY1 (3,3,65)
```

```
      CALL REALPL (66,66,3)
      C(67)=C(66) +3.0
      IF(C(55)-C(67))1,1,2
    1 C(64)=C(55)
      GO TO 3
    2 C(64)=C(67)
    3 CONTINUE
C     OIL SYSTEM GOES HERE
      CO(34)=C(34)
      C(34)=C(64)-(C(46)+3.0)
      CALL REALPL(35,35,34)
      CALL GAIN (36,36,34)
      CALL ADDER (37,37,35,36,0)
       CALL REALPL (86,86,37)
      CALL ADDER(38,38,-86,87,0)
      CALL ADDER(39,39,-38,41,0)
      CALL ADDER(89,89,39,-90,0)
      CALL GAIN(40,40,39)
      CALL ADDER(41,41,-40,42,0)
       CO(81)=C(81)
       CO(80)=C(80)
      C(80)= C(38)*0.00141 +3.0
      C(81)=0.00141*C(41)+3.0
      CALL CMPLXPL(43,43,80)
      CALL CMPLXPL(44,44,81)
      CALL ADDER (45,45,44,-43,0)
      CALL REALPL(46,46,45)
C    WATER SYSTEM
       CO(5)=C(5)
      C(5)=C(14)+15.0
      CALL CMPLXPL (33,33,5)
      CALL ADDER  (24,24,-33,32,97)
      CALL CMPLXPL(84,84,24)
      CALL GAIN(25,25,84)
      CALL REALPL(26,26,84)
      CALL ADDER (27,27,25,26,0)
      CALL DELAY1 (2,2,27)
      CALL CMPLXPL(28,28,2)
      CO(4)=C(4)
      C(4)=0.000114*(C(93)+C(28))+3.0
      CALL CMPLXPL(29,29,4)
      CALL REALPL  (30,30,29)
      CALL ADDER(31,31,57,-30,0)
      CALL REALPL (32,32,31)
C    WATER LEVEL
      CALL ADDER(91,91,50,-92,0)
      CALL REALPL(6,6,91)
      CALL REALPL(7,7,91)
      CALL CMPLXPL(8,8,7)
      CALL ADDER (9,9,8,-6,0)
      CALL REALPL (10,10,28)
      CALL CMPLXPL(11,11,10)
      CALL REALPL(12,12,89)
      CALL CMPLXPL(13,13,12)
      CALL DELAY1 (1,1,13)
      CALL ADDER (14,14,9,11,1)
C    STEAM PRESS
      CALL REALPL(83,83,91)
      CALL CMPLXPL (15,15,91)
      CALL REALPL (16,16,15)
```

```
 CALL ADDER (17,17,15,16,0)
CALL REALPL(82,82,89)
 CALL REALPL (18,18,82)
CALL REALPL (19,19,18)
CALL ADDER (20,20,18,-19,0)
CALL REALPL (21,21,28)
 CALL CMPLXPL (22,22,21)
CALL ADDER (23,23,20,-17,-22)
RETURN
END
END
```

```
C     DATA FOR 90 PER CENT FULL POWER DELTA PLANT

-48        NUMBER OF BLOCK DATA CARDS
01   .36
02 0.25
03 0.045
06 1.26 E-06
07 1.726E-04   0.55
08 1.0        1.645      7.69
10 2.0  E-06
11  1.0       .508        1.59
12 2.375E-05  0.5
13 1.0       0.5         .25
15 .00005    .882        .396
16 1.985
18 .00806    .4
19 1.188      1.41
21  1.0 E-07
22  1.0       0.06        0.01
25 1.26
26 0.1
28 9360.       .531       .781
29 19.2       2.62        19.2
30 0.222       0.222
32 14.7        29.4
33  4.0        2.4        4.0
35 0.392
36 2.82
40 0.0445
43  30.3       5.9        30.3
44  30.3      5.9        30.3
46 30.87      29.4
49  50.0      .6         50.
51 .944
53 73.6       29.4
55 250.       9.5       250.
57 19.2       2.62        19.2
58  333.3      13.3       333.3
59 .106
61 100.       7.9        100.
62 .89
65 2.5        2.5
66 30.87       29.4
69 950.        1.0
70 2.0        0.56        2.0
72 .000865    0.1575
75 1.134
82 1.0
83 1.0
84 1.25        0.675      1.25
86 24804.      31.2
2            NUMBER OF CURVES
09          BREAK PTS      BOILER PRESSURE        CURVE 1
  0.0                      1200.
 34000.                    1203.
 56000.                    1208.
```

```
  66500.                   1211.
  100000.                  1226.
  120000.                  1237.
  140000.                  1250.
  152000.                  1259.
  167000.                  1272.
44    BREAKPOINTS  SUPERHEATER PRESSURE DROP   CURVE 2
   0.0                        0.0
    20000.               1.0
  28000.               2.0
     34000.             3.0
   39000.                4.0
  45000.                      5.2
  48000.                     6.0
  50000.                     6.5
  52000.                     7.0
  54000.                     7.4
  56000.                     8.0
  58000.                     8.6
  60000.                  9.2
  62000.                 10.0
  64000.                 10.5
  66000.                 11.1
  68000.                 12.0
  70000.                 12.8
  74000.                 14.0
  76000.                 15.0
  78000.                 15.9
  80000.                 16.6
  84000.                 18.0
  86000.                 19.0
  88000.                 20.0
  90000.                 21.0
  94000.                 23.0
  96000.                 24.0
  98000.                 25.0
 100000.                 26.0
 108000.                 30.0
 117000.                 35.0
 120000.                 37.0
 125000.                 40.0
 130000.                 44.0
 140000.                 50.0
 145000.                 54.0
 150000.                 59.0
 160000.                 66.0
 165000.                 70.0
 170000.                 74.0
 180000.                 84.0
 190000.                 92.0
 200000.                101.0
-01
50 152000.
0.01          TIME INCREMENT
55.0         TOTAL TIME
1.
0.2                    PLOT TIME
0194         VARIBLES TO BE PRINTED
030BRIEN GH DELTA SYSTEM (90 PER)(NEG RAMP)4-4
9994  AIR FLOW(C 94)(PERCENT) VS TIME (SEC)
```

9928 DELTA FEEDWATER FLOW (C-28) (LBS/HR) VS TIME
9989 DELTA FUEL FLOW (C-89) (LBS/HR) VS TIME (SEC)

Appendix IV

Subroutines INVAL and DIAGRAM and Data for Cruising Conditions for Ten to Ninety Per Cent Full Power Simulation of the Complete Boiler

```
      SUBROUTINE INVAL
      DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
     1COOO(99),COOOO(99),T(10),X1(900),X2(900),X3(900),
     2Y1(900),Y2(900),Y3(900),
     3ITITLE(12),JTITLE(12),KTITLE(12),
     4X(15,40),Y(15,40)
      COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X,Y,Y1,Y2,Y3
C     C(50) IS READ FROM IC CARD
       C(42)=15900.
       C(97)=15.
      C(92)=C(50)
      CALL CURVE (2,47,50)
      CALL CURVE (1,76,50)
      CALL ADDER (48,48,76,23,-47)
      C(77)=0.04*C(48)-33.0
      C(49)=C(77)
      C(52)=C(97)-C(49)
      C(53)=(G(53)/H(53))*C(52)
      C(78)=0.0001142 *C(50)+3.0
      C(57)=C(78)
      C(54)=C(53)+C(57)
      C(55)=C(54)
      C(67)=C(55)
      C(66)=C(67)-3.0
      C(3)=C(66)*(H(66)/G(66))
      C(65)=C(3)
      C(79)=C(65)
      C(75)=C(79)/.254
      C(72)=C(75)/G(75)
      C(56)=C(55)-C(67)
      CALL CURVE(4,73,72)
      CALL CURVE (9,88,72)
      CALL CURVE (5,74,88)
      C(71)=C(72)
      C(70)=C(71)/C(73)
      C(69)=C(70)
      C(68)=C(69)
      CALL CURVE(6,63,68)
      C(61)=C(63)
      C(60)=C(61)
      C(58)=C(56)*(G(58)/P(58))
      C(51)=C(58)*G(51)
      C(59)= C(60)-C(51)
      IF(C(55)-C(67))1,1,2
    1 C(64)=C(55)
      GO TO 3
    2 C(64)=C(67)
    3 CONTINUE
C     FUEL OIL FLOW (GF) FOR CRUISING SPEED =4140.
      C(46)=C(64)-3.0
      C(45)=C(46)*H(46)/G(46)
      C(39)=C(45)/0.00141
      C(41)=C(42)-G(40)*C(39)
      C(40)=C(39)*G(40)
      C(90)=C(39)
      C(38)=C(41)-C(39)
       C(87)=C(38)
      C(81)=0.00141*C(41)+3.0
```

```
C(80)= C(38)*0.00141 +3.0
C(44)=C(81)
C(43)=C(80)
C(5)=C(14)+15.0
C(33)=C(5)
C(93)=C(50)
C(85)=C(93)+C(28)
C(4)=0.000114*C(93)+3.0
C(29)=C(4)
C(30)=C(29)
C(31)=C(57)-C(30)
C(32)=C(31)*(G(32)/H(32))
C(24)=C(97)+C(32)-C(33)
C(25)=C(24)*(G(25)/P(25))
RETURN
 END
```

```
      SUBROUTINE DIAGRAM
      DIMENSION G(99),H(99),P(99),Q(99),R(99),C(99),CO(99),COO(99),
     1COOO(99),COOOO(99),T(10),X1(900),X2(900),X3(900),
     2Y1(900),Y2(900),Y3(900),
     3ITITLE(12),JTITLE(12),KTITLE(12),
     4X(15,40),Y(15,40)
      COMMON G,H,P,Q,R,C,CO,COO,COOO,COOOO,T,X1,X2,X3,X,Y,Y1,Y2,Y3
       IF (C(99)-23.0) 10,10,20
   10 C(50) =16600. +(5915.0*C(99))
   20 CONTINUE
      CALL CURVE (2,47,50)
      CALL CURVE (1,76,50)
      CALL ADDER (48,48,76,23,-47)
        CO(77)=C(77)
      C(77)=.04*C(48)-33.0
      CALL CMPLXPL(49,49,77)
       C(97)=15.
      CALL ADDER (52,52,97,-49,0)
      CALL REALPL (53,53,52)
       CO(78)=C(78)
      C(78)=.0001142*C(50)+3.0
      CALL CMPLXPL(57,57,78)
      CALL ADDER (54,54,53,57,0)
      CALL CMPLXPL (55,55,54)
      CALL ADDER (56,56,55,-67,0)
      CALL CMPLXPL (58,58,56)
      CALL CURVE (9,88,72)
      CALL GAIN (51,51,58)
      IF(C(51)-30.0   )1000,1000,2000
 1000 IF(C(51)-0.0)3000,3000,4000
 2000 C(51)=30.0
      GO TO 4000
 3000 C(51)=0.0
 4000 CONTINUE
      CALL REALPL (59,59,58)
      IF(C(59)-30.0)1100,1100,2100
 1100 IF(C(59)-0.0)3100,3100,4100
 2100 C(59)=30.0
      GO TO 4100
 3100 C(59)=0.0
 4100 CONTINUE
      CALL ADDER(60,60,51,59,0)
       IF (C(60)-30.) 1200,1200,2200
 1200 IF(C(60)-0.) 3200,3200,4200
 2200 C(60)=30.
       GO TO 4200
 3200 C(60)=0.
 4200 CONTINUE
      CALL CMPLXPL (61,61,60)
      CALL DERIVA (62,62,61)
      CALL ADDER (63,63,61,62,0)
C     THE AIR SYSTEM GOES HERE
       CALL CURVE (3,68,63)
      CALL REALPL(69,69,68)
      CALL CMPLXPL (70,70,69)
      G(71)=C(73)
      CALL GAIN (71,71,70)
      G(72)=C(74)
      H(72)=C(74)
      CALL REALPL(72,72,71)
```

```
      CALL CURVE (4,73,72)
      CALL CURVE (5,74,88)
      CALL GAIN (75,75,72)
       CO(79)=C(79)
       C(79)=C(75)*.254
      C(94)=C(75)*1.2
      CALL REALPL(65,65,79)
      CALL DELAY1 (3,3,65)
      CALL REALPL (66,66,3)
      C(67)=C(66)+3.0
      IF(C(55)-C(67))1,1,2
    1 C(64)=C(55)
      GO TO 3
    2 C(64)=C(67)
    3 CONTINUE
C     OIL SYSTEM GOES HERE
      CO(34)=C(34)
      C(34)=C(64)-(C(46)+3.0)
      CALL REALPL(35,35,34)
      CALL GAIN (36,36,34)
      CALL ADDER (37,37,35,36,0)
       CALL REALPL (86,86,37)
      CALL ADDER(38,38,-86,87,0)
      CALL ADDER(39,39,-38,41,0)
      CALL ADDER(89,89,39,-90,0)
      CALL GAIN(40,40,39)
      CALL ADDER(41,41,-40,42,0)
       CO(81)=C(81)
       CO(80)=C(80)
      C(80)= C(38)*0.00141 +3.0
      C(81)=0.00141*C(41)+3.0
      CALL CMPLXPL(43,43,80)
      CALL CMPLXPL(44,44,81)
      CALL ADDER (45,45,44,-43,0)
      CALL REALPL(46,46,45)
C   WATER SYSTEM
       CO(5)=C(5)
      C(5)=C(14)+15.0
      CALL CMPLXPL (33,33,5)
      CALL ADDER  (24,24,-33,32,97)
      CALL CMPLXPL(84,84,24)
      CALL GAIN(25,25,84)
      CALL REALPL(26,26,84)
      CALL ADDER (27,27,25,26,0)
      CALL DELAY1 (2,2,27)
      CALL CMPLXPL(28,28,2)
      C(85)=C(93)+C(28)
      CO(4)=C(4)
      C(4)=0.000114*(C(93)+C(28))+3.0
      CALL CMPLXPL(29,29,4)
      CALL REALPL  (30,30,29)
      CALL ADDER(31,31,57,-30,0)
      CALL REALPL (32,32,31)
C   WATER LEVEL
      CALL ADDER(91,91,50,-92,0)
      CALL REALPL(6,6,91)
      CALL REALPL(7,7,91)
      CALL CMPLXPL(8,8,7)
      CALL ADDER (9,9,8,-6,0)
      CALL REALPL (10,10,28)
```

```
      CALL CMPLXPL(11,11,10)
      CALL REALPL(12,12,89)
      CALL CMPLXPL(13,13,12)
      CALL DELAY1 (1,1,13)
      CALL ADDER (14,14,9,11,1)
C    STEAM PRESS
      CALL CMPLXPL (15,15,91)
      CALL REALPL (16,16,15)
       CALL ADDER (17,17,15,16,0)
      CALL REALPL(82,82,89)
       CALL REALPL (18,18,82)
      CALL REALPL (19,19,18)
      CALL ADDER (20,20,18,-19,0)
      CALL REALPL (21,21,28)
       CALL REALPL (22,22,21)
      CALL ADDER (23,23,20,-17,-22)
       C(95)=C(39)/13.1
       C(96)=(C(93)+C(28))/1660.
      RETURN
      END
      END
```

```
C   DATA FOR 10-90 PER CENT FULL POWER IN 23 SECONDS

-48      NUMBER OF BLOCK DATA CARDS
01   .36
02 0.25
03 0.045
06  1.12 -06
07 2.805 -05  0.3141
08  1.0       0.763      1.588
10  5.54- 07
11  1.0       0.422       0.495
12  1.86 -04   2.22
13  1.0       0.76        0.4
15 .000368  1.4545     .0627
16 .028
18 7.87  -03 .0445
19 1.732     1.76
21 1.73  -06
22 1.0       0.0445
25 1.26
26 0.1
28 9360.      .531      .781
29 19.2      2.62        19.2
30. 0.222     0.222
32 14.7       29.4
33  4.0       2.4        4.0
35 0.392
36 2.82
40 0.0445
43  30.3     5.9        30.3
44  30.3     5.9        30.3
46 30.87     29.4
49  50.0     .6         50.
51 .944
53 73.6      29.4
55 250.      9.5       250.
57 19.2      2.62        19.2
58  333.3     13.3       333.3
59 .106
61 100.      7.9        100.
62 .89
65 2.5       2.5
66 30.87      29.4
69   1.0        1.0
70 2.0       0.56       2.0
72 .000865   0.1575
75 1.134
82 1.0
83 1.0
84 1.25       0.675      1.25
86 24804.     31.2
09
10       BREAK PTS      BOILER PRESSURE       CURVE  1
  0.0                   1200.
16600.               1201.
  34000.                1203.
  56000.                1208.
  66500.                1211.
  100000.               1226.
```

```
  120000.              1237.
  140000.              1250.
  152000.              1259.
  167000.              1272.
40  PRESSURE DROP ACROSS THE SUPERHEATER
   0.0                    0.0
16600.              1.0
  28000.            2.0
     34000.          3.0
   39000.             4.0
  45000.                 5.2
  48000.                6.0
  50000.                6.5
  52000.                7.0
  54000.                7.4
  56000.                8.0
  60000.             9.2
  62000.            10.0
  64000.            10.5
  66000.            11.1
  68000.            12.0
  70000.            12.8
  74000.            14.0
  76000.            15.0
  78000.            15.9
  80000.            16.6
  84000.            18.0
  90000.            21.0
  94000.            23.0
  98000.            25.0
 100000.            26.0
 108000.            30.0
 117000.            35.0
 120000.            37.0
 125000.            40.0
 130000.            44.0
 140000.            50.0
 145000.            54.0
 152000.            59.0
 160000.            66.0
 165000.            70.0
 170000.            74.0
 180000.            84.0
 190000.            92.0
 200000.           101.0
 10          BREAKPONTS FOR CURVE 3   GB*   VS   PQ
  -100.              1440.
 3.0                 1440.
  5.0               1440.0
  6.0               1600.0
  10.25             2800.0
  14.3              4300.0
  18.5              6400.0
  22.75             9200.0
  27.0             12800.0
  1000.           12800.
 08 BLOWER GAIN VS QB                                    CURVE 4
 6.2                .00436
 6.35               .00436
 20.8               .00762
```

```
34.7                      .00755
49.2                      .00735
63.2                      .00538
74.8                     .00488
100.                     .00488
10 BLOWER SPEED VS TIME CONSTANT (1000 RPM)            CURVE 5
0.0                        .04
1.0                        .04
2.0                       .0585
3.0                       .09
4.0                        .128
5.0                       .182
6.0                         .214
7.0                       .272
8.0                       .3015
20.0                      .3015
10
0.0                        3.0
1440.                      3.0
  1440.                       5.0
  1600.                       6.0
  2800.                       10.25
  4300.                       14.3
  6400.                       18.5
  9200.                       22.75
  12800.                      27.0
  18000.                      31.3
08  GPR VS N
0.0                       2.73
    3.0                      2.73
    4.                       2.23
    5.                       1.77
    6.                       1.26
    7.                       1.0
    8.                       1.0
   10.                       1.0
08  INTEGRAL GAIN VS N
0.0                        0.498
  3.0                         .498
  4.0                         .498
  5.0                         .498
  6.0                         .397
  7.0                         .397
  8.0                         .444
 10.0                         .444
08 BLOWER SPEED VS QB                                 CURVE 10
6.2                        1.8
6.35                       1.8
20.8                      2.912
34.7                      4.14
49.2                       5.107
63.2                      6.708
74.8                       7.480
100.                       7.480
-01
50 16600.
  0.01
50.0                        TOTAL TIME
1.
.1
```

```
0196
03 J FENICK BOILER 10-90 WITH CR
9994  PERCENT OF AIR
9995 PERCENT OF FUEL
9996 PER CENT OF WATER
```

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